

UArctic Climate Interventions
Draft Atmosphere Assessment Report for Review¹
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Note: Changes to criteria

The Atmosphere assessment team has proposed changes to two of the criteria used in the original rapid assessment. Both changes will be considered by the project management team for future assessments:

1. “Cost to Benefit Comparison” has been changed to “Cost considerations and operational feasibility”. The team considered the original wording too broad and potentially misleading, as a cost-benefit comparison would imply consideration of wider climatic, social, governance, and economic costs and benefits that fall beyond the scope of this assessment. This criterion is not ranked.
2. “Amount of attention within the academic community, public media, and industry” has been changed to “Google Scholar and funding metrics”. The team considered these indicators to provide more transparent and comparable measures of research and funding activity. They are indicative rather than comprehensive and are not intended as a formal evaluation of the level of attention given to each intervention.

¹ This report represents the views of the Atmosphere assessment team and does not necessarily reflect those of UArctic.

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46 Arctic Marine Cloud Brightening

47 Issue being addressed

48 Roughly one-third of the incoming solar radiation is directly reflected back into space by
49 the Earth's atmosphere and surface albedo. Clouds play an important role in this,
50 though their effect is double-edged, as water droplets can also interfere with outgoing
51 longwave radiation, thereby contributing to the greenhouse effect. Over open water,
52 clouds can make a particularly big difference as the albedo of the water is below 0.1,
53 thereby absorbing most of the sun's energy. In the Arctic, loss of sea ice and snow
54 cover has reduced surface albedo, increasing solar absorption and amplifying regional
55 warming, making cloud reflectivity a potentially important feedback process.

56 Description of the technology/ measure

57 Arctic Marine Cloud Brightening (MCB) seeks to enhance cloud albedo over the
58 northern high latitude oceans during the summer months by increasing the amount,
59 lifetime, and reflectivity of overlying clouds. MCB uses the Twomey effect (Twomey,
60 1977), whereby a larger number of smaller water droplets scatter more incoming solar
61 radiation than fewer, larger droplets (Latham et al., 2012). Clouds form as water vapour
62 condenses around small airborne particles, or cloud condensation nuclei (CCN); MCB
63 proposes the deliberate introduction of fine sea salt aerosol to increase CCN
64 concentrations within stratocumulus and other low-level cloud decks. The most
65 commonly discussed method to achieve this is to generate these particles by spraying
66 filtered seawater into the marine boundary layer, the lowest part of the atmosphere
67 directly influenced by the ocean's surface, producing submicron droplets that evaporate
68 to leave salt crystals suspended in the air. In addition to brightening the clouds, these
69 additional aerosols may also extend cloud lifetime by slowing coalescence and reducing
70 precipitation. However, this effect is critically dependent on the background
71 concentrations of existing particles and meteorological conditions, making it less
72 effective in polluted areas. Although greater cloud cover slightly reduces outgoing
73 longwave radiation, modelling studies indicate a net shortwave cooling effect in summer
74 (e.g., Latham et al., 2014; Wood et al., 2024). During the Arctic winter, when incident
75 sunlight is minimal, MCB operations would cease; however, larger-scale MCB
76 operations in other parts of the world could affect the Arctic through long-distance
77 teleconnections (Dipu et al., 2021) and impacts on general circulation patterns.

Technological readiness

Score: Low-Medium

Confidence: Medium

Aerosols contribute to cloud formation, and the effect of aerosols from ships has been observed over tracks of ocean vessels (Hobbs et al., 2000), and studies on such “inadvertent” MCB provide valuable analogues for MCB (Patel and Shand 2022). Globally, this effect could potentially be large, with studies estimating the radiative effect between 0 and -0.5 W m^{-2} (Quaglia and Vioni (2024); Hansen et al., 2025). Translating that into a change of surface temperature is complicated, but the effect of new regulations on the sulfur content of shipping fuels is estimated to unmask 0.06–0.22K of warming (Yuan et al., 2024). Several programs have sought to expand research into MCB, including laboratory experiments (Cooper et al., 2014). In 2014, Neukermans et al. designed a spray device that used seawater as the salt source. As an alternative distribution method, Claudel et al. (2023) suggested using UAVs to seed clouds but this dispersion mechanism hasn’t been investigated in more detail.

Recent prototype tests of effervescent nozzle systems indicate that sea-salt aerosols can now be generated at rates and particle sizes suitable for small-scale outdoor perturbation experiments. A single nozzle can produce approximately 10^{12} s^{-1} sea-salt aerosols within a 30–1000 nm size range, suggesting that vessel-based platforms could potentially achieve the particle generation rates required for first-phase MCB field trials (Harrison et al., 2025). Indeed, active research continues in Australia, where scientists seek to explore the possibility of using MCB to reduce coral bleaching and cool the waters around the Great Barrier Reef (Tollefson, 2021); however, these experimental studies are still ongoing to substantiate the observed effects. A new research project by the Cambridge Centre for Climate Repair and Delft University will also specifically examine the potential relevance of MCB for more regional applications.

Designing field campaigns capable of resolving detectable signals in low-sunlight conditions in the Arctic is crucial rather than extrapolating results from other parts of the world as current model results show that uncertainties in aerosol-cloud interactions mean that the sea salt aerosol mass required for cooling varies greatly (Henry et al. 2025 <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025EF006508>). Also, for current sprayer designs, energy consumption is as of now prohibitively large.

Real-world implementation would likely involve a network of overlapping plumes from many mobile platforms (globally 10,000 to 100,000 sprayers; Wood, 2021), which would take time to design and poses logistical challenges. The IPCC AR6 WG1 notes that many uncertainties remain regarding MCB, especially because climate models do not adequately represent the relevant cloud processes (2021, chapter 4). For example, Hoffmann and Feingold (2021) found that small differences in particle seeding size could significantly affect the effect of MCB. Additionally, characterisation of the

background is still poor, which has implications for other tradeoffs, e.g., the energy required to produce particles within a certain size range, and warrants further study.

Scalability

Score: Low-medium **Confidence:** Medium

Scalability is assessed as low-medium, as physically possible, but operationally highly uncertain. Arctic MCB would entail large fleets of vessels operating throughout the summer season, but to date, these ships exist only on paper, and it remains uncertain whether the measure is truly scalable (National Research Council, 2015). Wood (2021) estimates that 10,000 to 100,000 vessels would need to operate 'over the majority of the 54% of the Earth's surface that is over ocean and remote from land' to offset the radiative forcing associated with a doubling of atmospheric CO₂. Moreover, while global-scale modelling suggests that increased sea-salt aerosol flux would result in brightened clouds and reduced Arctic temperatures (Henry et al., 2025), large uncertainties remain in models' representations of clouds, especially at high latitudes where observations are limited. A further complication in the Arctic is that Arctic meteorological conditions (mixed-phase clouds, variable boundary-layer stability) likely constrain the number of effective seeding days, further limiting practical scalability.

Recent experimental analysis (e.g., Wood et al., 2024) indicates that while small-scale, ship-based plume experiments are feasible, scaling beyond single-vessel deployments faces significant operational, logistical, and governance constraints, requiring coordination, transparency, and international oversight. Power and maintenance demands for coordinated multi-vessel campaigns remain high, particularly because energy-efficient prototype nozzles are not yet available. Manshausen et al. (2022) note that invisible ship tracks can generate measurable radiative forcing, implying that detectable regional effects could occur at scales smaller than previously assumed, or even outside of the primary target region, but these remain highly uncertain and depend on meteorology and background aerosol loading. Also, feedback effects within the climate system could potentially limit scalability to avoid side effects such as impacts on large-scale circulation.

Timeliness for near-future effects

Score: Medium-High **Confidence:** Medium

Prototype nozzle systems and ship-based process experiments indicate that the first outdoor perturbation studies of MCB adjacent applications (i.e., marine fogging) are technically feasible within the current decade. Such trials could generate useful data on aerosol-cloud interactions and radiative responses well before 2030, particularly under targeted regional campaigns (e.g., Great Barrier Reef studies). However, scaling these efforts to sustained, climate-relevant interventions remains distant, dependent on both

demonstrable cloud-brightening efficacy and the development of appropriate governance frameworks, especially in multi-country-affected regions like the Arctic. In the near term, progress is most likely to come from short-duration, process-level experiments designed to inform models rather than produce measurable climatic effects.

Potential to make a difference in Northern + Arctic

Score: Medium **Confidence:** Medium

Multiple modelling studies suggest that MCB could generate cooling over the Arctic, including through atmospheric and oceanic energy transport, when implemented elsewhere. Rasch et al. (2009) and Parkes et al. (2012) found that polar MCB could substantially increase summer sea ice extent in a CO₂-doubled world. Latham et al. (2012, 2014) similarly showed that enhanced cloud albedo could reduce summer sea ice loss and contribute to stabilising permafrost and adjacent ice-sheet margins. More recent simulations (Kim et al., 2020; Zhao et al., 2020) reinforce the potential for regional cooling across the Arctic and sub-Arctic, including the Sea of Okhotsk and northern Eurasia.

However, all these effects remain based purely on models and highly idealised setups (Feingold et al., 2024). They also depend strongly on cloud regime, aerosol injection efficiency, background meteorological conditions and scenarios of future emissions. Contemporary ensemble studies highlight large uncertainties in cloud microphysical feedbacks and atmospheric circulation responses, especially under Arctic mixed-phase conditions. Real-world effectiveness would depend on seasonal cloud availability and aerosol transport, which remain poorly constrained in Arctic simulations and will include effects from all the confounding factors. Increased cloud ice formation in a warmer future could decrease the liquid water path in the cloud, thereby amplifying the positive climate feedback.

Potential to make a global difference

Score: Medium **Confidence:** Medium

Multiple model studies have shown that MCB could exert a substantial effect on radiative forcing, although its overall effectiveness in reducing temperatures remains highly uncertain (National Research Council, 2015). Simulations suggested that 10,000-100,000 sprayers will be needed to mask approximately 3°C of warming (Wood et al., 2021). Large ensemble modelling by Stjern et al. (2018) found a mean global temperature reduction of about -0.96°C under RCP4.5 when the cloud condensation nuclei of all marine low clouds are increased by 50%. The review by Lawrence et al. (2018) reported that limited knowledge about key microphysical and dynamical processes involved results in a large uncertainty in the maximum cooling achievable

using MCB (0.8 to 5.4 W m⁻²). The IPCC AR6 WG1 report assessed a comparable range (1–5 W m⁻²) but assigned low to medium confidence, citing major uncertainties in cloud-aerosol feedback.

Recent studies highlight that the global impact of MCB would depend strongly on spatial targeting and temporal coordination of interventions - for example, whether seeding is focused over persistent stratocumulus decks in the subtropical Pacific and Atlantic (Wood et al., 2024). Emerging work using optimisation and AI-assisted modelling (e.g., Hirasawa et al., 2023) suggests that patterned forcing strategies could enhance global cooling efficiency, though these remain theoretical. A better representation of cloud microphysics and dynamical cloud-feedbacks (e.g., impacts on mesoscale circulation) are necessary prerequisites to gauging the effectiveness of MCB.

Cost considerations and operational feasibility

(Not scored, see note above)

The costs of operationalisation for MCB at scale remain highly uncertain but are generally expected to be low relative to the potential climate and socioeconomic costs of inaction, with around \$1–10 billion per year as estimated by the National Research Council [NASEM, 2015].

However, estimates for large-scale operational concepts vary widely. In a Guardian article, Sir David King (CCR Cambridge) suggested that an Arctic-focused MCB fleet of 500–1,000 vessels could require an initial investment of around £40 billion and annual continuation costs of £10 billion (Anthony, 2022). These figures exclude monitoring, governance, and potential environmental remediation costs, which could be significant. Given the remaining uncertainties around effectiveness, regional impacts, and regulatory feasibility, the benefit-cost ratio cannot yet be robustly quantified, but is anticipated to be low.

Likelihood of environmental risks

Score: Medium

Confidence: Medium

Like other solar radiation modification (SRM) measures, MCB could alter regional precipitation patterns and the hydrological cycle, and thus it could impact the frequency and likelihood of associated hazardous events (IPCC, 2021, Chapter 4). Large ensemble modelling by Stjern et al. (2018) found a global precipitation decrease of approximately 2–3 %, while Bala et al. (2012) reported similar, though somewhat smaller, effects than those associated with land-based albedo modification. This will offset the increase in global precipitation due to global warming (IPCC, 2014). The National Research Council (NASEM, 2015) noted potential reductions in surface light availability that could affect photosynthesis and local ecosystems, as well as possible

impacts on ocean circulation and carbon sequestration (Partanen & Bala, 2016; Lauvset & Bala, 2017). Other studies suggest that widespread injection of sea-salt aerosol may influence tropospheric ozone and methane lifetime, with minor but non-negligible air-quality implications (Horowitz & Bala, 2020).

Because MCB is inherently spatially patchy, producing uneven radiative forcing between seeded and unseeded regions, strong gradients could induce teleconnected changes in atmospheric circulation and precipitation (Kravitz et al., 2018). Few comprehensive studies have examined such downstream or cross-hemispheric effects (Ricke et al., 2021). Modelling of Arctic MCB's influence on mid-latitude circulation and precipitation (especially over Europe and Asia) is still limited, although a recent study did not find consistent remote changes in precipitation when doing MCB in the Arctic (Henry et al. 2025 <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025EF006508>).

Potential beneficial side effects include regional cooling, reduced tropical cyclone intensity (Latham et al., 2012b), and decreased crop-failure risks (Parkes et al., 2015), though such outcomes remain speculative. Emerging work explores whether AI-guided control or adaptive targeting (Hirasawa et al., 2023) might eventually reduce unintended effects, but this remains at the conceptual stage

Effects on local/ Indigenous communities

Score: Unknown **Confidence:** –

There is currently no direct evidence on how Marine Cloud Brightening (MCB) activities might affect local or Indigenous communities. Diamond et al. (2022) and others emphasise the need for collaboration among physical scientists, ecologists, social scientists, and ethicists to identify potential social, cultural, and livelihood risks. Arctic MCB research would likely intersect with Indigenous territories (e.g., Inuit, Saami, coastal fisheries), underscoring the importance of co-design rather than one-way consultation. Frameworks such as the Aarhus Convention and the Espoo Convention already require early stakeholder engagement and transboundary consultation. Possible concerns include impacts on marine productivity or fish stocks if local biogeochemical processes are affected, which could, in turn, influence subsistence and commercial fisheries. Recent governance analyses highlight that procedural inclusion, prior consultation, and recognition of Indigenous and local rights should be treated as prerequisites for any outdoor experimentation - illustrated by good-practice elements in the Great Barrier Reef prototypes, which emphasised engagement with Indigenous Traditional Owners, and by lessons from the 2024 Alameda MCB test, which was cancelled after a unanimous City Council vote citing transparency and lack of prior consultation (Burns and Talati, 2025).

Ease of reversibility

Score: Easy

Confidence: High

The direct effects of MCB would only last a few days, and aerosol itself might indeed be removed on a timescale of days/weeks. However, climate effects could linger, e.g., changes to ocean/atmospheric circulation or ecosystems, due to long-term MCB deployment.

Risk of termination shock

Score: High

Confidence: High

The C2G2 risk analysis report on SRM (2022) states that 'A sudden and sustained termination of a large amount of SAI [stratospheric aerosol injection] or MCB under a high GHG emission background would cause a rapid increase in temperature and precipitation at a rate that far exceeds that predicted for future climate change without SRM.' MCB is vulnerable to operational disruptions or political discontinuities, as its climatic influence depends on the continuous maintenance of aerosol plumes. Note that changes to ocean/atmospheric circulation or ecosystems resulting from long-term MCB deployment would persist longer.

Suitability within current legal/ governance structures

Score: Medium

Confidence: Medium

MCB falls within a grey area of existing environmental law. While domestic cloud-seeding activities are already regulated in many jurisdictions, there are no binding international mechanisms governing marine-based SRM research or deployment. The Australian MCB experiments demonstrate that small-scale, process-level studies can proceed under national environmental and maritime regulations without triggering international consultation.

At larger scales, however, activities would almost certainly fall under the scope of the Convention on Biological Diversity (CBD), which restricts climate intervention activities that may affect biodiversity to small-scale scientific research subject to prior assessment and governance. They could also raise issues under the London Convention and Protocol and the Espoo Convention, depending on their potential for transboundary effects.

Governance reviews (e.g., C2G2, 2020; Roche et al., 2025) conclude that while existing frameworks provide procedural principles - such as environmental assessment, transparency, and public participation - they offer no coherent oversight for transboundary or climate-scale interventions. Early dialogue among states, regulators, and researchers is therefore essential to clarify responsibilities and avoid fragmented or unilateral experimentation.

MCB is not explicitly mentioned in the BBNJ Agreement text, but MCB research or deployment in areas beyond national jurisdiction would fall within its scope via the treaty's environmental impact assessment and area-based management tools provisions. The BBNJ may be relevant where biodiversity impacts from MCB are expected in areas beyond national jurisdiction. MCB in exclusive economic zones or coastal waters would be governed by UNCLOS and regional/sectoral agreements.

Google scholar and funding metrics

(Not scored, see note above)

MCB remains the second-most-discussed SRM technique after stratospheric aerosol injection (SAI) and has attracted significant attention across both scientific and public domains. A search for MCB on Google Scholar yields 8,720 results, including 4,850 studies linking them to the Arctic. Several large projects have been funded across the world, such as over the Great Barrier Reef in Australia, an MCB Project in California, USA, which is a collaborative effort between the University of Washington, SilverLings, and PNNL backed by the Gates Foundation. The UK's Advanced Research and Invention Agency has also funded several projects relevant to MCB. VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment, The Geoengineering Model Intercomparison Project (GeoMIP) coordinates climate modelling of SRM and often includes MCB as one of its core experiments. This shows that, overall, academic and policy interest remains high, but so does public controversy, underscoring that social acceptance is now as decisive for MCB's future trajectory.

Snowfall Enhancement

Issue being addressed

With the exception of some regions such as Antarctica, many mid- and high-latitude areas have experienced declining snowfall and shorter snow-cover duration, with implications for albedo, runoff timing, ecosystems, and water resources (Qing et al., 2025). In a warming climate, rain-on-snow events are projected to become more frequent in many cold regions, further altering snowmelt dynamics and increasing risks of floods and other hydrological hazards (Maina and Kumar, 2025).

Description of the technology/ measure

Precipitation enhancement and weather modification have a long history. Although cloud seeding can be discussed in the context of climate intervention, previous and existing activities are best understood as local or regional water-management and adaptation measures rather than tools to significantly modify global climate.

Glaciogenic cloud seeding aims to enhance precipitation from cold clouds by introducing ice-nucleating particles, often silver iodide (AgI), into supercooled clouds that contain liquid water at temperatures typically between about -5 and -15 °C. The AgI particles act as artificial ice nuclei, promoting the formation of ice crystals that can grow by vapor deposition and riming and then fall out of the cloud as snow, provided that ground level temperatures don't induce melting. Glaciogenic seeding thus potentially increases the total precipitation compared to natural conditions but quantifying results in a statistically robust manner remains a challenge.

Operational programs deploy AgI either from aircraft or from ground-based generators. Modern research programs, such as the Seeded and Natural Orographic Wintertime Clouds – Idaho Experiment (SNOWIE), combine radars, aircraft in-situ measurements, and dense snow-gauge networks to track seeded plumes and quantify seeding-induced snowfall under carefully selected conditions. There have been sparse references to the use of cloud seeding over Arctic and Northern areas as a means of countering some of the effects of climate change. Some have suggested using it specifically over glaciers (see Stabilizing Glaciers by Cloud Seeding). Artificial snow production, as used in many ski resorts, is generally treated as an adaptation measure in its own right, rather than as a form of snowfall enhancement climate intervention, and is therefore not included in this assessment (Rice et al., 2022; Scott et al., 2003).

Technological readiness

Score: Medium/ High

Confidence: High

The technology can be considered prototype demonstrated, system complete, and system proven, however detecting and attributing significant snowfall changes remains

a challenge, particularly with regard to translating clearly detectable microphysical and local snowfall signals into robust, statistically significant enhancements at the basin or seasonal scale. The Wyoming Weather Modification Pilot Project (WWMPP) and its subsequent evaluation, for example, found that while ensemble modeling suggested a 5% enhancement of precipitation in seedable cases, traditional statistics could not reject the null hypothesis of “no seeding effect,” implying that any seasonal-scale increase (~1–2% of annual precipitation) is small relative to natural variability (Rasmussen et al., 2018). Recent reviews conclude that wintertime orographic cloud seeding can likely enhance snowfall by few and perhaps up to 10–15% in ideal seedable conditions, but that effects are highly conditional and remain difficult to verify for operational programs. The Snowy Hydro project (<https://www.snowyhydro.com.au/generation/cloud-seeding/>) in NSW, Australia, did operational cloud seeding to generate snow from 2013 -2023 and ceased to operate, as benefits did not outweigh the high costs.

Scalability

Score: Low

Confidence: Medium

Glaciogenic cloud seeding only works when suitable clouds are present, i.e., clouds that contain sufficient supercooled liquid water, lie within a suitable temperature range, and are favorably aligned with terrain and prevailing winds. Because only a limited fraction of all storms and cloud volumes can be effectively seeded, and because individual seeding operations produce relatively modest additional accumulations (typically at most a few millimeters liquid equivalent over large areas in documented case studies), the efficiency of scaling saturates quickly and remains strongly sub-linear.

Timeliness for near-future effects

Score: Low

Confidence: Medium

The technology for glaciogenic cloud seeding already exists, but it is not certain if it would be able to make a significant climate impact, even if it were sufficiently scaled up. While cloud seeding may serve as a short- to medium-term adaptation tool in some areas, it is unlikely to offset broader snow-related impacts of warming across the northern or Arctic regions.

Potential to make a difference in Northern + Arctic

Score: Low

Confidence: Medium

Studies do not yet demonstrate sustained regional impacts on mass balance or surface albedo across wider Arctic or sub-Arctic domains. Given the difficulties around scalability, it seems unlikely that snowfall over the entire region could be enhanced significantly.

Northern and Arctic regions pose additional constraints: storms often occur in harsh, remote environments with limited infrastructure, and low temperatures can limit the availability of supercooled liquid water, a prerequisite for effective seeding. Given these physical and logistical barriers, plus the modest magnitude of seeding effects observed elsewhere, it appears unlikely that cloud seeding could meaningfully enhance snowfall across the broader Arctic, though niche applications on specific high-value glaciers or catchments may still be investigated.

Potential to make a global difference

Score: Low **Confidence:** High

The seeding would likely have a primarily local effect and be insignificant to be detected at a global scale.

Cost considerations and operational feasibility

(Not scored, see note above)

Snowfall enhancement can be considered technically and operationally feasible in selected mountain watersheds, especially where existing infrastructure, high water value, and frequent seedable winter storms make modest additional snowpack economically useful. However, costs are not trivial once forecasting, generators or aircraft, monitoring, permitting, environmental compliance, and independent evaluation are included. Cost-effectiveness is highly site-specific and uncertain because suitable climatic conditions and added snowfall is episodic, difficult to verify, and generally low or modest. The Snowy Hydro case is a useful example: operational seeding ended because rising costs outweighed benefits, despite long experience with the technology.

Likelihood of environmental risks

Score: Low **Confidence:** Low

Environmental risks are considered limited, with site-specific effects restricted to the deployment location. Silver iodide (AgI) has been used in cloud-seeding experiments for over 70 years, and available evidence suggests limited environmental or health risks at current use levels, although risks from wider deployment remain uncertain (GAO, 2024). Uncertainties remain regarding ecological effects under expanded deployment, cumulative silver/iodine deposition, off-target redistribution, and altered hydrological extremes remain relevant uncertainties (Maina and Kumar, 2025).

Effects on local/ Indigenous communities

Score: Mixed **Confidence:** Low

Could be considered potentially mixed or context-dependent. It could provide local benefits for water supply, hydropower, winter recreation, or snow-dependent livelihoods,

but effects on Indigenous and local communities would depend on where, when, and how snowfall changes. For reindeer herding, snow quality, timing, ice layers, and depth may matter as much as total snow amount (Rasmus et al., 2016, Rosqvist et al., 2022). Concerns include redistribution of precipitation, downstream or downwind effects, lack of consent, distrust, and uneven benefit-sharing, requiring transparency, local consultation, and meaningful Indigenous participation (Kasuri et al., 2026, Eira et al., 2018).

Ease of reversibility

Score: Easy **Confidence:** High

The direct intervention stops when seeding stops, with no persistent atmospheric forcing or long-lived deployed effect, however, any added snowfall may persist seasonally in snowpack and affect downstream runoff (French et al., 2018).

Risk of termination shock

Score: Low **Confidence:** Medium

Ending seeding would remove any incremental local snowfall benefit, but would not cause abrupt global or regional change in climate.

Suitability within current legal/ governance structures

Score: Medium **Confidence:** Medium

Cloud seeding is already legal and regulated in several jurisdictions, and the 1977 Environmental Modification Convention (ENMOD) Convention mainly restricts hostile or military environmental modification. WMO stresses best-practice research design, environmental monitoring, ethics, and public acceptance.

Snowfall enhancement may provide a historical analogue for SRM governance, showing how small-scale atmospheric modification has proceeded for decades with limited oversight, uneven transparency, and persistent attribution challenges, with lessons for future SRM field experiments (Simon, 2024).

Google scholar and funding metrics

(Not scored, see note above)

316 hits on Google Scholar in April 2026 for “Snowfall enhancement”. 67 of those have been published since 2022. Searching for Snowfall enhancement weather modification yields 20,000 hits, with 7450 since 2022. There is no reliable global estimate for cumulative operational or research spending specifically on snowfall enhancement.

Arctic Seasonal Stratospheric Aerosol Injection

Issue being addressed

The most studied method of SRM is stratospheric aerosol injection (SAI). Aerosols are solid or liquid particles which remain suspended in the air, and some aerosols such as sulfates are particularly efficient at reflecting solar radiation, and thus reduce global temperatures. Aerosols injected in the stratosphere can stay there for 1-2 years, and would need to be continuously injected to maintain the cooling effect.

Description of the technology/ measure

Stratospheric aerosol injection (SAI) is an idea to inject particles in the stratosphere to reduce the amount of incoming solar energy (Rasch et al., 2008; Irvine et al., 2016). The principle behind SAI is well understood as it is analogous to some naturally occurring volcanic eruptions which have been consistently observed to cool global temperatures over year-timescales if they deposit material high enough into the atmosphere (Robock et al., 2013; IPCC AR6 WG1, chapter 4). Although multiple aerosol types (e.g., calcite and diamond) have been suggested for SAI, most studies focus on SO₂, or sulphuric acid injections. Due to the high seasonality of sunlight in the higher latitude regions, it is optimal to inject SO₂ in the spring, allowing the sulfate to form in the summer of each hemisphere, and thus maximise the amount of sunlight reflected (Lee et al., 2021). One advantage of injection at high latitudes is that the stratosphere is lower allowing existing aircraft to reach it (Duffey et al. 2025). However, it is worth noting that more aerosols would be needed to reach a certain amount of cooling compared to tropical injection, and that high latitude SAI remains a global climate intervention as all parts of the globe would be affected.

Technological readiness

Score: Medium

Confidence: –

At the moment, SAI studies are mostly limited to model simulations. There have recently been several initiatives that have prompted major debate within the community, but so far, no major or substantial outdoor tests have been conducted (Low et al., 2022). However, the Israeli-American company Stardust have announced that small-scale outdoor experiments will be conducted “as soon as April 2026” (Hiar & Mathiesen 2025). And the UK’s Advanced Research and Innovation Agency (ARIA) has funded five projects with a controlled, small-scale outdoor experiment component, one of which is relevant to SAI but will not involve the release of any particles (ARIA 2026).

There have been several suggestions for how to inject SO₂ (or other reflective particles) in the stratosphere, with the most commonly discussed is specifically designed aircraft to reach the stratosphere (e.g. Bingaman et al., 2020), though existing aircraft could reach the stratosphere at higher latitudes where the stratosphere is lower (Duffey et al.,

2025). Although higher injections would require less mass injection to achieve the same amount of cooling, there are strong trade-offs in terms of costs and safety hazards (Smith et al., 2022).

Estimates for deployment timelines vary widely. The most ambitious timeline would be Stardust who claim to be able to deploy by 2030 (Meyer 2025). As mentioned above, for high latitude low altitude deployment, one could use existing aircraft. However, for high-altitude deployment, one would have to build new aircraft which would take at least a decade.

Scalability

Score: High

Confidence: –

The scalability of SAI is limited in one sense as the effectiveness of injections decreases with increased injection rates (Kleinschmitt et al., 2018). These effects are, however, most pronounced at high injection rates that would be required for the complete mitigation of high forcing scenarios. The evolution of the sulfate particle size distribution within an airplane wake, however, is uncertain.

The injection of aerosols in the stratosphere at low latitudes are dispersed globally by stratospheric winds, and would ensure a global coverage and global reduction of surface temperatures. If aerosols were to be specifically injected at higher latitudes, they would have more focused effects over those parts as stratospheric dynamics move the particles polewards, but still cool the whole planet. Although estimates vary, it is estimated that a fleet of hundreds of aircraft would be needed to achieve significant surface cooling (Smith and Wagner, 2018).

Timeliness for near-future effects

Score: Medium

Confidence: –

Although there are currently no existing infrastructure for SAI, the development of a new kind of aircraft to release aerosols in the stratosphere is likely to be a relatively straightforward task especially for a high latitude low altitude deployment (Smith and Wagner(2018), Duffey et al. 2025). and Smith et al. (2022) consider a high latitude injection program to be a 'decadal time-scale project'. A lot would depend on the proposed SAI injection strategy and goal. As mentioned in the Technological Readiness section, estimates for deployment timelines vary widely. Unlike most other methods addressed in this document however, one cannot deploy SAI only within one's national jurisdiction, which adds additional governance and geopolitical barriers.

Potential to make a difference in Northern + Arctic

Score: High **Confidence:** –

Model studies have consistently shown that SAI could cool surface temperatures and slow or reverse the melting and thawing of the cryosphere in the Arctic (Robock et al., 2008; Berdahl et al., 2014; Chen et al., 2020, 2023; Lee et al., 2023). This cooling could furthermore have multiple other benefits for the region. For example, Tang et al. (2023) show that it would reduce wildfires (see Wildfire Management).

Irvine et al. (2018), however, note that the effects of SAI are different from simply reversing GHG forcing. While SAI would reduce sea level rise by reducing ocean heat uptake and reducing Greenland ice sheet melting, it is unclear to what extent it could reduce the melting of Antarctic ice shelves as it is driven by deep ocean waters (Goddard et al. 2023). Yue et al. (2021) equally found that the Icelandic Vatnajökull ice cap's melt can be reduced somewhat by SAI, although it remains relatively insensitive to solar radiation management. Concerning the wider cryosphere, Zhao et al. (2017) find SRM could also slow melt in other areas like in the “Third Pole” region.

Potential to make a global difference

Score: High **Confidence:** –

Multiple model studies and historical analogues of volcanic eruptions show SAI could reduce global temperatures when initiated (IPCC AR6 WG3, chapter 14). The amount of cooling would be dependent on injection strategies and on the total amount of sulfur injected, with larger injection amounts achieving a progressively lower efficacy (Kleinschmitt et al., 2018).

While the most recent studies use scenarios which limit warming to 1.5C in middle-of-the-road greenhouse gas emission scenarios (Lee et al. 2025), previous studies used SAI to maintain temperatures at 2020 levels in a high-emission scenario offsetting up to 5C by 2100 (Tilmes et al. 2018). It is worth noting that these are for global SAI scenarios (i.e. injection at the equator or subtropics), and that injection at high latitudes and low altitudes would require about 50% more sulfur dioxide to achieve the same amount of global cooling (Duffey et al. 2026).

Cost considerations and operational feasibility

(Not scored, see note above)

Compared with the effects of global warming, the operational costs appear small. Smith (2020) estimates the direct costs of SAI to be around \$18 billion per degree of global cooling per year, for a tropical injection. This does not account for the governance or monitoring costs, nor does it account for the potential environmental damages caused by the SAI program itself.

576 There is no direct cost estimate of high latitude low altitude SAI using existing aircraft to
577 our knowledge.

578 **Likelihood of environmental risks**

579 **Score:** Medium **Confidence:** –

580 Some of the major objections against SAI relate to this measure's possible
581 environmental and ecological effects. The expected ones are still relatively under-
582 researched (Zarnetske et al., 2020) and there may be several unknown risks related to
583 global deployment.

584 A first expected consequence of SAI would be an effect on rainfall patterns and a
585 weakening of monsoons (Bala et al., 2008; Krishnamohan and Bala, 2020; Riky, 2023),
586 though this seems to be ameliorated through hemispherically symmetric deployment
587 away from the equator (Zhang et al. 2024, Henry et al. 2024). Nalam et al. (2018) and
588 Lee et al. (2023) found that SAI in the Arctic alone would significantly alter precipitation
589 patterns around the globe but that this could be largely balanced out by a mirrored
590 cooling of the Antarctic.

591 Although there have been fears of acid rain due to the use of sulfates, the earliest
592 estimates on SAI by Budyko (1974) indicated that the total amounts of deposited
593 material are negligible in comparison to other anthropogenic emissions, while a recent
594 study indicated that even in the high emission pathways, global sulfur depositions would
595 not vary much from present levels (Visioni, 2020). However, sulfate particles would be
596 deposited in previously pristine regions, which could be a concern for large amounts of
597 cooling.

598 The use of sulfate particles could also impact stratospheric ozone levels (Tilmes et al.,
599 2008). The WMO ozone assessment states 'While existing studies do not suggest a
600 deepening of the ozone hole beyond that already experienced, current shortcomings in
601 model representation of required processes limit confidence in the results.' (Haywood &
602 Tilmes 2022). It is also worth noting that ozone impacts are also dependent on
603 deployment strategy, such as the latitude of injection (Zhang et al. 2024)

604 Sustained deployment could have significant impact on the lower and middle
605 stratosphere, and UNEP (2023) writes this could have 'unknown consequences for the
606 environment on and near Earth's surface.'

607 Since SAI would reduce the amount of available energy for photosynthesis on the
608 Earth's surface and in the oceans, the IPCC 2021 AR6 WG1 report states it has
609 medium confidence that SAI would 'cause a reduction in plant and soil respiration and
610 slow the reduction of ocean carbon uptake due to warming.'

Effects on local/ Indigenous communities

Score: Unknown **Confidence:** –

There is a lack of research on the potential effects of SAI on local communities. Of the many understudied topics, the potential impact of SAI on human health has only started to be explored (Tracy et al., 2022), with Carlson et al. (2022), for example, finding that SAI would cause trade-offs in terms of malaria distributions.

Certain events also reveal that there is significant skepticism against SAI amongst some communities. This showed especially clearly in the 2021 protest against the Harvard SCoPEX group in North Sweden by Sami and environmental activists. In addition, statements like the assertion by Smith et al. (2022) that ‘an SAI program with global benefits that would entail deployment directly overhead of far less than 1% of the world’s population and nearly none of its agriculture may prove an easier sell to a skeptical world than a full-on global deployment’, further highlight the need for more research into the opinions and possible effects of potential SAI deployment in the Arctic and Northern regions.

Ease of reversibility

Score: – **Confidence:** –

The lifetime of sulfate particles in the stratosphere is around 1-2 years (Kremser et al., 2016). Hence, once the injection stops, the particles would naturally fall out, however, the cooling effect would dissipate over longer timescales because of the larger heat capacity of the ocean.

Risk of termination shock

Score: High **Confidence:** –

A major issue with SAI is the potential of a termination shock when the technology is abruptly halted (Jones et al., 2013; IPCC AR6, WG1, chapter 4; UNEP 2023; Parker and Irvine 2018). The C2G2 risk analysis report on SRM (2022) states clearly that ‘A sudden and sustained termination of large amount of SAI or MCB under a high GHG emission background would cause a rapid increase in temperature and precipitation at a rate that far exceeds that predicted for future climate change without SRM.’ For the Arctic specifically, Berdahl et al. (2014) show that in an RCP4.5 scenario, a sudden termination would negate all geoengineered benefits in terms of retained snow and ice within a decade.

Suitability within current legal/ governance structures

Score: Low **Confidence:** –

A main objection that many opponents of SAI have is that they assert it would be ungovernable, as countries and actors would dispute over target temperatures and

struggle to find common ground with regard to compensation of the negative effects of SAI (Biermann et al., 2022). Others, including NASEM (2021) and UNEP (2023), instead argue for further research into the governance of climate interventions and climate intervention research. There are already several governance proposals (Reynolds, 2019), and further research has been conducted, perhaps most prominently by the Carnegie Climate Geoengineering Governance Initiative (C2G2). UNEP (2023), however, urges increasing emphasis on the need to include previously excluded voices, especially in the global South, and that decision be made ‘in a globally inclusive, equitable and transparent manner’.

Given that SAI aerosols would rapidly disperse across borders and hemispheres, and that radiative and hydrological impacts would be globally distributed, SAI is inherently transboundary. As such, existing environmental, air pollution, and transboundary harm principles would not provide sufficient legal authority for unilateral deployment (Roche et al., 2026). Most legal analyses therefore conclude that any consideration of SAI deployment - even at moderate scales - would require new multilateral agreements or explicit mandates to avoid conflicts with existing international law, including the no-harm rule, the duty to consult affected states, and obligations under treaties such as The Convention on Long-range Transboundary Air Pollution, The Convention on Biological Diversity, and UNCLOS.

Google scholar and funding metrics

(Not scored, see note above)

SAI is the most researched and written about climate intervention concept. Since 2021, several private-sector activities related to SAI have emerged. These include the UK-based Stratospheric Aerosol Transport and Nucleation (SATAN) project (2021/2022) and the US-based company Make Sunsets, both of which have released small amounts of sulphur dioxide into the atmosphere via high-altitude balloons. The Israeli-US enterprise Stardust Solutions has reportedly conducted initial hardware test flights and has raised a total of \$75 million to develop its proprietary aerosol, monitoring, dispersal, and modelling capabilities (Meyer 2025).

There is also an increasing number of academics worldwide doing modelling work on SAI and studying the governance issues surrounding research and deployment. Funding has increased markedly in the last few years. SRM360, for example, reports that more than \$30 million dollars per year has been spent on the SRM field as a whole in 2023 and 2024 (SRM360 2025).

Space-based Solar Radiation Modification

Issue being addressed

Space-based approaches seek to intervene outside the atmosphere. In principle, this could reduce global temperatures without introducing additional material into the atmosphere, although it would not address the underlying causes of climate change or associated impacts such as ocean acidification.

Description of the technology/ measure

Space-based SRM concepts aim to reduce incoming solar radiation before it reaches the Earth's atmosphere by placing large-scale optical structures in space. Typically, these would be near the Sun–Earth L1 Lagrange point – a position approximately 1.5 million km from Earth where the gravitational forces of the Earth and Sun balance, allowing objects to remain in a relatively stable position between them. This location provides a continuous line of sight between the Sun and Earth, allowing persistent interception of solar radiation.

Most proposed systems operate by reflecting, refracting, or diffracting incoming sunlight using very large, lightweight structures. These may take the form of mirrors, sunshades, or distributed arrays of thin-film elements (see Baum et al., 2022, for a summary of all ideas). Fundamentally, these designs rely on materials engineered to interact with or scatter solar radiation at visible wavelengths (~400–600 nm), enabling a minor decrease of incoming energy while allowing outgoing infrared radiation from Earth to escape.

Although a wide range of concepts have been proposed – including mirrors or lightsails (Kennedy et al., 2013), swarms of small spacecraft (Ellery, 2016), and more speculative approaches such as inflatable “bubbles” (MIT Senseable City Labs) or dust clouds (Bromley et al., 2023) - their underlying objective is similar: to reduce total incoming solar radiation by approximately 1–2%, which is broadly sufficient in principle to decrease radiative forcing by 4 W/m² (2.4–4°C), comparable to counteracting a doubling of atmospheric CO₂ (Weber & Kabbej, 2023; Lazard et al., 2025).

These systems would require extraordinarily large effective surface areas – potentially on the order of one million square kilometres – either as single structures or as vast distributed networks of smaller elements, maintained in position near L1. Alternative locations, such as geostationary orbit, have also been proposed owing to their greater proximity to Earth; however, these would introduce significant challenges, including non-uniform and transient shading, interference with existing satellite infrastructure, and heightened risk of collision and space debris (Baum et al., 2022). Consequently, these are less suitable than L1 for large-scale, continuous solar attenuation.

Technological readiness

Score: Low

Confidence: High

Space-based SRM remains at a very low level of technological readiness. While the underlying physical principles are relatively well understood, recent assessments consistently conclude that the engineering, deployment, and cost challenges are prohibitive based on current or near-term capabilities.

A recent briefing by The Royal Society (2025) indicates that, although space-based reflectors may be among the few SRM approaches capable in principle of achieving substantial global cooling, they are also associated with the highest technical barriers and likely associated costs (\$1–20 trillion) of any proposed method. These barriers relate primarily to the scale of material deployment required, the need for sustained launch capacity, and the complexity of maintaining large structures or distributed systems in space. This challenge is reflected in estimates suggesting that some concepts would require on the order of 10^{10} kg of material per year – hundreds of times more mass than has been launched into space to date – or rely on highly speculative approaches such as the extraction and deployment of lunar dust (Bromley et al., 2023).

Earlier assessments reach similar conclusions. UNEP (2023) notes that development timescales are likely to be significantly longer than for atmospheric approaches, while NASEM (2015) did not consider space-based SRM in detail due to the scale of the associated technological challenges. Expert surveys further suggest that, while the concept is broadly understood, there remains considerable uncertainty regarding its practical feasibility (Baum et al., 2022). Consequently, quantitative estimates and the degree of uncertainty of costs, materials, and logistics required illustrate the low technological readiness.

Scalability

Score: Low

Confidence: Medium

In theory, space-based SRM is not physically constrained by available space, and its radiative effect would scale approximately with the surface area deployed. However, scalability in this context depends on the ability to expand deployment in a timely, affordable, and operationally feasible manner. In practice, scalability is severely constrained by engineering, logistical, and economic factors – as discussed in the technological readiness section. Increasing scale would require proportional increases in material production, launch capacity, and orbital deployment, all of which remain far beyond current capabilities (Bromley et al., 2023; Royal Society, 2025). The requirement to deploy and maintain extremely large structures composed of distributed networks, likely composed of smaller elements, implies sustained, large-scale

756 operations over decades to centuries. However, the capacity to deliver that scaling in
757 practice is highly constrained.

758 **Timeliness for near-future effects**

759 **Score:** Low **Confidence:** Medium

760 Space-based SRM is unlikely to deliver near-term climate effects. The primary
761 constraint lies in the time required to design, manufacture, launch, fund, and deploy
762 sufficient material to achieve meaningful radiative impact. Most assessments conclude
763 that these processes would take decades at a minimum, given current technological
764 and industrial capabilities, with additional time likely required to address the
765 international coordination and governance challenges associated with such a global
766 intervention (NASEM, 2015; Keith et al., 2020; UNEP, 2023; The Royal Society, 2025).
767 Even under optimistic assumptions, achieving climate-relevant cooling would require
768 sustained deployment at scale over long periods. As a result, space-based SRM is not
769 considered a viable option for near-term climate risk reduction.

770 **Potential to make a difference in Northern + Arctic**

771 **Score:** High **Confidence:** Medium

772 Reducing solar radiation at the L1 point modulates incoming radiation for the entire
773 Earth, rather than specific regions. As such, Space-based SRM would produce global
774 changes in incoming solar radiation and would thus likely have a corresponding effect in
775 the Arctic. The Arctic would be affected as part of a broader global response, rather
776 than through targeted intervention.

777 **Potential to make a global difference**

778 **Score:** High **Confidence:** High

779 In principle, space-based SRM could produce a global cooling effect by reducing
780 incoming solar radiation. Most assessments conclude that a reduction of approximately
781 1–2% in insolation would be sufficient to offset the radiative forcing associated with a
782 doubling of atmospheric CO₂ (Weber & Kabbej, 2023; Lazard et al., 2025). However,
783 while the physical mechanism is well understood, the ability to achieve such effects in
784 practice remains highly uncertain due to the technological and logistical constraints
785 discussed above.

786 **Cost considerations and operational feasibility**

787 (Not scored, see note above)

788 Space-based SRM is widely considered to be exceptionally expensive (The Royal
789 Society, 2025). Early order-of-magnitude estimates suggested costs in the range of tens
790 to hundreds of billions of US dollars (Keith, 2000; Angel, 2006), while more recent

assessments place potential costs in the range of US\$1–20 trillion (Baum et al., 2022). These wide-ranging estimates reflect the uncertainty in system design and the scale of the engineering challenge – including material production, launch capacity, and long-term operation and maintenance over decades. As a result, high cost and operational complexity are consistently identified as primary barriers to the development of space-based SRM (NASEM, 2015; UNEP, 2023).

Likelihood of environmental risks

Score: Low **Confidence:** Low

Like all climate-relevant SRM approaches, space-based SRM would alter the Earth's energy balance by reducing incoming solar radiation. This could affect precipitation patterns, the hydrological cycle, ecosystems, photosynthesis, solar energy generation, and regional climate conditions. These system-level risks are not unique to space-based SRM, but arise from the broader climatic effects of reducing insolation.

Space-based SRM may avoid some of the direct environmental risks associated with atmospheric approaches, because it would not introduce particles or aerosols into the atmosphere. It would therefore avoid risks linked to stratospheric chemistry, ozone impacts, and cloud microphysical uncertainty. However, space-based approaches could introduce distinct risks, including uneven or transient shading depending on system design and operation, with potential implications for ecosystems, solar energy production, and human activities (SAPEA, 2024). Other risks include launch-related impacts, collision and debris risks, and consequences of system failure or loss of control. Overall, while space-based SRM may have lower direct atmospheric perturbation risks than SAI or MCB, its absolute environmental risks remain uncertain and potentially significant if deployed at climate-relevant scale.

Effects on local/ Indigenous communities

Score: Unknown **Confidence:** Low

Space-based SRM would operate at a global scale, producing broadly distributed climatic effects rather than targeting specific locations. As such, it would not directly intervene in particular regions or communities. However, global climate responses are unlikely to be uniform, and changes in temperature, precipitation, or other climate variables could still affect regions and populations differently. The extent to which local or Indigenous communities might be disproportionately impacted therefore remains uncertain.

Ease of reversibility

Score: Unknown

Confidence: Low

In terms of climate response, space-based SRM would be highly reversible. Reducing, reorienting, or terminating a shading system would rapidly restore incoming solar radiation, with effects occurring on timescales of days to weeks, unlike atmospheric approaches – particularly SAI – where particles persist.

However, the operational reversibility of such systems is more uncertain. Large-scale structures or distributed networks positioned near L1 would require active control, and intervention could be complex if systems were damaged, misaligned, or partially uncontrolled. As a result, while the radiative effect may be quickly reversible in principle, the practical ability to reliably and safely achieve this remains uncertain.

Risk of termination shock

Score: High

Confidence: Medium

Space-based SRM presents a more complex termination-shock profile than short-lived atmospheric approaches. In principle, a large space-based sunshade or distributed reflector system could provide relatively stable radiative forcing over long periods, particularly if designed with redundancy, modular replacement, and ongoing maintenance capacity. Unlike SAI or MCB, it would not depend on the continuous replenishment of short-lived particles in the atmosphere. In some long-term transition scenarios, space-based SRM has therefore been discussed as a possible way to reduce dependence on sustained atmospheric SRM in the future (see for example IAA 2026).

However, this does not remove the risk of termination shock. If space-based SRM were deployed at climate-relevant scale and then rapidly reduced, disrupted, or destroyed, the loss of cooling could still produce rapid warming. The risk would be particularly significant if societies had become dependent on the intervention while greenhouse gas concentrations remained high. Large L1-based systems may also be vulnerable to failure, loss of control, or deliberate disruption, and rapid redeployment after major damage would likely be extremely difficult (Keith et al., 2020).

Overall, space-based SRM may offer greater long-term stability than atmospheric approaches if maintained successfully, but the consequences of abrupt loss at scale could remain severe. The risk of termination shock is therefore best characterised as uncertain but potentially high, rather than simply low.

Suitability within current legal/ governance structures

Score: N/A

Confidence: Medium

SRM, particularly at the level of deployment, raises significant governance challenges, including issues of international coordination, consent, and legitimacy.

Space-based SRM would not fall into a legal vacuum. The 1967 Outer Space Treaty and related space-law frameworks would be directly relevant, including rules on state responsibility, authorisation and supervision of private space activities, registration, consultation over harmful interference, liability, and space debris (Neef, 2025). However, these rules were not designed for deliberate climate intervention and would not amount to a comprehensive governance framework for space-based SRM.

In particular, existing liability rules are likely to be better suited to physical damage caused by space objects than to indirect climatic or environmental harms. Given the very low technological maturity of space-based SRM, any detailed assessment of the suitability of current governance frameworks for field experimentation or deployment remains highly speculative.

Google scholar and funding metrics

(Not scored, see note above)

Space-based SRM has received relatively limited attention in the scientific literature compared to atmospheric approaches. Reviews suggest that only a small proportion of climate intervention research focuses on space-based methods, with most work remaining conceptual and exploratory in nature (Baum et al., 2022).

While the underlying physical principles are well understood, there is little evidence of sustained experimental or programme-level research, reflecting the significant technical and cost barriers associated with these approaches.

Cirrus Cloud and Mixed-Phase Cloud Thinning (CCT/MCT)

Issue being addressed

High-altitude cirrus clouds and lower mixed-phase clouds both play major roles in regulating the Earth's radiation budget. Cirrus clouds - composed purely of ice crystals - typically have a net warming effect because they efficiently trap outgoing longwave radiation (Wolf et al., 2023). Mixed-phase clouds, containing both supercooled liquid droplets and ice particles, also contribute to radiative warming during Arctic winter, yet remain poorly understood and challenging to represent in climate models (Korolev et al., 2017). Thinning ice-containing clouds has been proposed as a potential means of increasing longwave heat loss to space during winter months. However, with the drivers for cloud ice formation (e.g., the availability of ice-supersaturated regions for cirrus clouds or concentrations of ice nucleating particles for mixed-phase clouds) being highly uncertain, the evaluation of these methods remains challenging (Murray et al., 2021; Eastham et al., 2025).

Description of the technology/ measure

CCT and MCT are related concepts that aim to change the optical properties and lifetime of these clouds by introducing ice-nucleating particles (INPs).

In CCT, INPs are released into high-altitude ice clouds. These particles trigger the formation of fewer but larger ice crystals, which sediment out more quickly, shortening cloud lifetime and reducing their efficiency in trapping outgoing longwave radiation (Storelvmo et al., 2013). CCT is expected to be most effective in very cold, high-latitude winter conditions when cirrus clouds have a strong net warming effect (Gruber et al., 2019).

MCT operates on a similar microphysical principle but targets lower-altitude mixed-phase clouds, which contain both supercooled liquid droplets and ice crystals (Korolev & Milbrandt, 2022). Seeding with INPs such as silver iodide can shift the cloud from mixed-phase to ice-dominated conditions, accelerating precipitation processes and thinning the cloud layer (Villanueva et al., 2022).

Technological readiness

Score: Low

Confidence: High

Research on CCT/MCT remains at a very early conceptual stage, dominated by modelling (e.g., Storelvmo et al., 2013; Villanueva et al., 2022).

For CCT, substantial uncertainties persist around cirrus formation pathways and the influence of natural and anthropogenic aerosols on ice nucleation. Tully et al. (2022) argue that additional observational evidence is needed before further modelling

advances can meaningfully reduce uncertainty. It is not clear how clouds would be seeded and whether regions susceptible to seeding are ubiquitous enough.

For MCT, mixed-phase clouds remain one of the largest uncertainties in climate models and only a few peer-reviewed modelling studies (e.g., Villanueva et al., 2022) currently evaluate its potential effects. At a process-level, glaciogenic cloud-seeding techniques - e.g., as used for hail suppression - provide relevant analogues for weather modification scales, but not with regard to larger scale climate impacts.

Also, the practical method of delivering ice-nucleating particles for CCT or MCT is also unresolved, particularly in light of needing to identify suitable regions for seeding.

Scalability

Score: Low

Confidence: Medium-High

Both CCT and MCT require the presence of suitable conditions, i.e., ice-supersaturated regions with predominantly freezing of solution droplets for CCT and supercooled droplets in the case of MCT. Both cloud regimes have restricted spatial and temporal occurrence, which limits the applicability. Also there are large challenges in being able to identify target regions for seeding.

Timeliness for near-future effects

Score: Low

Confidence: Medium-High

Due to large uncertainties in effectiveness (particularly for CCT) and unresolved technological challenges, a comprehensive evaluation and the necessary potential technological developments are not expected within the next decade.

Potential to make a difference in Northern + Arctic

Score: Medium

Confidence: Low - Medium

CCT during winter at high latitudes is generally believed to be able to cause a cooling effect (Gruber et al., 2019). However, a recent study by Tully et al. (2022) using a more sophisticated model contradicts earlier studies and disputes that winter high-latitude strategies will significantly increase seeding efficacy.

For MCT, only one modelling study (Villanueva et al., 2022) shows a modest wintertime cooling effect in the Arctic, but this result has not yet been replicated or tested with alternative models.

Overall, while the conceptual basis for Arctic cooling exists, the current evidence remains weak, inconsistent, and highly model-dependent, suggesting only limited and highly uncertain potential for meaningful regional climate impact.

Potential to make a global difference

Score: Low

Confidence: Low - Medium

Some studies (Muri et al., 2014; Lohmann & Gasparini, 2017; Gasparini et al., 2020; Villanueva et al., 2022) found that CCT and MCT could have a cooling effect. However, other studies point out that CCT in particular might be associated with overseeding and highly uncertain cloud feedback effects, leading to an additional and undesired warming effect (Lohmann and Gasparini 2017; Liu and Shi (2021)). The complexities around cloud physics would also require further research into many potential side effects and interactions with other suggested measures. Kuebbeler et al. (2012), for example, found that stratospheric aerosol injection (SAI) could have an effect on cirrus clouds.

Cost considerations and operational feasibility

(Not scored, see note above)

CCT and MCT require continuous and repeated seeding over large areas to maintain radiative impact, as the lifetime of aerosol particles in the troposphere and lower stratosphere is on the order of days to weeks. Also, designing technology that enables suitable seeding strategies and effective monitoring would be a significant challenge.

Likelihood of environmental risks

Score: Unknown

Confidence: –

There have been very few studies on the potential environmental effects of CCT/MCT, e.g., to investigate the effect of CCT on the hydrological cycle. Kristjánsson et al. (2015) found CCT would enhance this cycle and lead to increased global precipitation. Changes in regional precipitation under CCT/MCT (but also in general), however, remain a challenge for climate models. Also, although deposition from MCT/CCT would be limited, all seeding agents would need to be evaluated also regarding their toxicity, e.g., in aquatic environments.

Effects on local/ Indigenous communities

Score: Unknown

Confidence: -

If effective, modest winter cooling could bring mixed outcomes for local and Indigenous communities: potential benefits (e.g., stabilisation of winter sea-ice conditions, support for traditional travel routes, reduced mid-winter rain-on-snow events) alongside possible disruptions (e.g., altered precipitation patterns, unpredictable impacts on subsistence hunting or herding).

988 **Ease of reversibility**

989 **Score:** Unknown **Confidence:** –

990 A more regional and short-term application would have less severe implications
991 compared to a climate-scale deployment that also influences cloud feedbacks and
992 circulation patterns, even beyond the primary region of deployment. However, currently
993 there are no studies quantifying these effects.

994 **Risk of termination shock**

995 **Score:** Low - Medium **Confidence:** Low - Medium

996 Based on current studies, these techniques have only a limited global cooling potential
997 and would require a longer ramp up, also due to needs for a highly sophisticated
998 deployment and monitoring strategy. As a result, the risk of a rapid rebound in
999 temperatures following cessation is considered relatively low.

1000 **Suitability within current legal/ governance structures**

1001 **Score:** Low **Confidence:** Medium

1002 Although CCT and MCT use techniques similar to operational cloud seeding, they would
1003 not fit within existing national or local weather-modification regulations. Cloud seeding is
1004 governed as a local weather intervention with limited spatial and temporal effects. By
1005 contrast, CCT/MCT aim to alter radiatively important cloud regimes at high latitudes and
1006 would be framed as climate interventions, requiring far more stringent governance
1007 arrangements. Existing cloud-seeding laws may offer procedural lessons (e.g.,
1008 permitting, monitoring, notification requirements), but they are not applicable
1009 frameworks for authorising or governing deliberate radiative modification.

1010 **Google scholar and funding metrics**

1011 (Not scored, see note above)

1012 Google Scholar: 3 dedicated, peer-reviewed publications since 2022; the amount of
1013 funding directly allocated to MCT/CCT is unknown but several projects have been
1014 funded by larger programs such as ARIA.

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