

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

The Ice Sheet assessment team proposed a new criterion, Outcome Reliability Score, will be considered by the project management team for future assessments.

The Outcome Reliability Score represents the ability for technology to actively anticipate outcomes—which depends heavily on our understanding of ice sheet processes which is limited in many cases. They scored this category with four different scores, U-UNDETERMINED meaning the effect of the proposed intervention is debated, unresolved or unconstrained at present. **1-UNCERTAIN, 2-Low, 3-Medium, 4-High.** A rank of Uncertain means that the effect of the proposed intervention is debated, unresolved, or unconstrained at present.

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

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Enhancing Snowfall Through Cloud Seeding

Cloud seeding involves dispersing ice-nucleating particles — most commonly silver iodide (AgI), but also potassium iodide, dry ice, or liquid propane — into clouds to promote ice crystal formation and enhance precipitation. The technique has been studied since the pioneering experiments of Schaefer and Langmuir in the 1940s, and was the subject of extensive military and agricultural research in subsequent decades, including the US Project Stormfury hurricane-modification program (Fleagle et al., 1974).

Cloud seeding does not create atmospheric moisture: it can only act on clouds that already contain supercooled liquid water, typically at temperatures between approximately -5°C and -20°C . Its potential is therefore bounded by the moisture already present — conditions that are largely absent over most of the Antarctic interior, though more common over Greenland. Artificially increasing that moisture is assessed separately (Assessment 10: Humidity Augmentation).

The glaciological rationale is that enhanced snowfall over accumulation zones could augment surface mass balance, offsetting dynamic mass loss from ice streams and calving. This reasoning encounters fundamental atmospheric and glaciological constraints. Antarctica receives less than 50 mm of precipitation equivalent per year in its interior, and this extreme aridity reflects the large-scale atmospheric circulation of the polar cell rather than a nucleation deficit. A secondary glaciological constraint, identified by Winkelmann et al. (2012), is that increased snowfall thickens and steepens ice sheets, potentially increasing gravitational driving stress and accelerating ice flow, which would offset an estimated 30–65% of the snowfall-driven mass gain.

While cloud seeding has been proposed for ice sheets, it is largely focused on Antarctica. The (relatively) more humid Antarctic coastal regions are the only conceivable setting, where added snowfall might thicken and strengthen ice shelves (Lockley et al., 2020). No study has proposed cloud seeding specifically for Greenland, although Lockley et al. (2020) combine it with albedo interventions (fresh snowfall brightens the surface), a mechanism that would be relevant in Greenland where surface melt accounts for roughly half of mass loss and seedable supercooled clouds do occur (Shupe et al., 2013).

The overall conclusion is that cloud seeding does not offer a credible pathway to meaningful ice sheet stabilization or sea level management.

Outcome Reliability

Score: Uncertain

Confidence: Medium

Cloud seeding's ability to increase snowfall over ice sheets is uncertain and likely negligible at relevant scales. After decades of experimentation since the 1940s, careful analysis of randomized seeding campaigns indicates possible precipitation increases ranging from essentially zero to more than 20% in suitable clouds (Flossmann et al., 2019), but effective seeding requires supercooled liquid water clouds — absent over most of polar Antarctica. Winkelmann et al. (2012) showed that increased snowfall thickens and steepens ice sheets, increasing ice flow and offsetting an estimated 30–65% of the snowfall-driven mass gain. The only glacier trial, on a small Chinese mountain glacier, reduced mass loss by 14–17% over a few days, largely through the albedo of fresh snow (Wang et al., 2020). No study has demonstrated a causal link between cloud seeding and meaningful ice sheet mass balance change.

Outcome Reliability is rated uncertain. The question of efficacy over ice sheets has never been tested and remains scientifically open, but the available evidence and physical reasoning suggest negligible effect.

Technological Readiness Level

Score: Low

Confidence: Medium

The seeding hardware itself is mature. Aircraft-mounted flares, ground-based generators, and dry-ice dispersal are operational in mid-latitude water-resource programs (TRL 7–9 in that setting), and field campaigns in wintertime mixed-phase clouds have directly observed seeding-induced ice growth and precipitation (Flossmann et al., 2019). However, seeding-induced snowfall that adds mass to an ice sheet or ice shelf, reduces that TRL score to Low (TRL 1-2). The concept has been formulated, but no experiment has validated seeding-induced snowfall over an ice sheet, and the system has not been tested for that purpose in a relevant environment. Basic characterization of polar cloud microphysics for seeding purposes is also lacking.

Greenland is the more plausible setting. Unlike most of the Antarctic interior, clouds containing supercooled liquid water occur over the Greenland Ice Sheet in every month of the year, most abundantly in summer (Shupe et al., 2013), so seedable clouds are at least present. Seeding has also been attempted there: in 1960, trials for the US Army Cold Regions Research and Engineering Laboratory over Greenland ice-cap airstrips dissipated supercooled whiteout clouds with dry ice, while silver iodide — the standard agent for precipitation enhancement — proved ineffective (Jiusto & Rogers, 1960). Those experiments aimed to clear clouds for aircraft rather than to increase snowfall, and their effects were local and short-lived. They show that seeding can alter Greenland clouds, not that it can add measurable mass to the ice sheet. No precipitation-enhancement trial has been conducted over Greenland or Antarctica.

The only published field trial of seeding for glacier preservation took place on the Muz
Taw Glacier in China's Sawir Mountains in August 2018, where ground-based silver
iodide generators were used to induce snowfall. The fresh snow raised surface albedo
and reduced glacier mass loss by 32–41 mm w.e. (14–17%) over the trial period, but the
authors describe the work as preliminary and the effect lasted days (Wang et al., 2020).
The trial demonstrates that seeding can add snow to a small mountain glacier when
suitable clouds are present; it does not demonstrate the technique at ice-sheet scale or
in polar conditions.

The rating is further bounded by the dependence on moisture. Over the Antarctic
interior, seeding has nothing to act on unless atmospheric moisture is first increased.

Scalability

Score: Low **Confidence:** High

Even in mid-latitude water-resource programs, extending seeding effects documented in
individual clouds to catchment scales remains unresolved: one assessment described it
as a “two orders of magnitude challenge” requiring about 6000 storms to be seeded
(Flossmann et al., 2019). Even with fleets of aircraft operating continuously, scaling
precipitation enhancement to the accumulation zones of polar ice sheets — spanning
millions of km² — is physically implausible. The spatial targeting problem is
compounded by the difficulty of controlling cloud seeding outcomes in time and space,
and by the requirement for supercooled liquid water clouds that are absent over most of
the Antarctic interior and intermittent over Greenland (Shupe et al., 2013).

Timeliness for Near-Future Effects

Score: Low **Confidence:** Medium

Cloud seeding could not make a meaningful difference to ice sheet mass balance within
20 years. The scientific knowledge base required to assess feasibility for polar
glaciological application does not exist; basic field experiments characterizing
atmospheric moisture availability and cloud microphysics in polar regions would be
required before any efficacy claims could be tested. Even if the technique produced
consistent precipitation enhancement, the lag between surface mass balance gains and
any measurable effect on dynamic ice loss and sea level would introduce further delays
of decades (Winkelmann et al., 2012).

Potential to Make a Difference in the Arctic/Northern Regions

Score: Low, **Confidence:** Medium

Arctic and sub-Arctic conditions offer marginally greater atmospheric plausibility for cloud seeding. Greenland's coastal regions receive higher precipitation, and moisture-bearing weather systems from the North Atlantic provide more favorable seeding substrates. Mountain glaciers in Alaska, Iceland, Svalbard, and Scandinavia experience richer moisture environments. For specific Greenland coastal regions, targeted cloud seeding under suitable weather windows is more physically imaginable, though effectiveness has not been demonstrated.

Lockley et al. (2020) note that surface melt accounts for approximately half of Greenland's present mass loss, and that albedo modification through fresh snowfall could in principle be beneficial — though this is a distinct mechanism from cloud seeding per se. The dominant drivers of Arctic ice loss remain ocean warming and surface energy balance under rising temperatures, processes not addressed by snowfall augmentation. The low rating reflects marginal improvement in atmospheric plausibility for Arctic contexts relative to Antarctica, while acknowledging that effectiveness remains undemonstrated and the dominant loss mechanisms are unaffected.

Potential to Make a Global Difference

Score: Low **Confidence:** High

Cloud seeding addresses the wrong mechanism for the glaciers most responsible for global sea level rise. Antarctic mass loss is dominated by ocean-forced dynamic discharge — entirely unaffected by snowfall enhancement. Feldmann et al. (2019) calculated that stabilizing the West Antarctic Ice Sheet by surface mass deposition alone would require adding approximately 7,400 Gt of snow over 10 years — roughly three times Antarctica's current annual precipitation. No cloud seeding or humidity augmentation program could approach this magnitude.

Wang et al. (2025) characterize snowfall-augmentation approaches as localized, surface-based interventions that cannot address the underlying drivers of ice loss. Even if technically achievable at regional scale, the magnitude of any potential glaciological effect is insufficient to produce a globally significant impact on sea level rise. The fundamental constraint — that dynamic discharge is driven by ocean heat, not atmospheric precipitation deficits — cannot be resolved by any precipitation enhancement approach.

Cost to Benefit Comparison

Score: Prohibitive **Confidence:** Medium

No reliable cost estimates exist for polar cloud seeding at scales relevant to ice sheet stabilization. Even for mid-latitude winter resource programs, the economic case is

unresolved: seeding individual mixed-phase clouds has been judge unlikely to be economically viable (Flossmann et al., 2019). Scaling to ice sheet catchments would require costs orders of magnitude higher, with continuous aircraft operations for decades and monitoring to detect any glaciologically meaningful signal amid natural variability. Expected benefit is undefined and unlikely to be detectable.

Brown et al. (2021) project global sea-flood damages of up to about US\$22 trillion per year by 2100 without additional adaptation, but cloud seeding does not approach the scale or certainty of effect required to meaningfully contribute to avoiding those costs. Cost-benefit is prohibitive.

Likelihood of Environmental Risks

Score: Some Risk

Confidence: Medium

Cloud seeding risks are real but limited in scope at conceivable polar scales. Silver iodide has generally been considered to have low bioavailability, but laboratory exposures at the reference concentration used in environmental monitoring reduced photosynthetic activity in freshwater phytoplankton and moderately reduced soil bacterial viability, suggesting effects on biota where seeding is repeated over the same area and the agent accumulates (Fajardo et al., 2016). Any introduction of foreign chemical agents into pristine polar environments raises concerns under the Madrid Protocol. Extra-area effects on precipitation are a recognized concern (Flossman et al., 2019): enhancing precipitation over one region may reduce it downwind, affecting sea ice formation, coastal ocean stratification, and ecosystem processes in ways that are difficult to predict.

The risk reflects impacts that could extend beyond the immediate deployment area but are bounded by the small scale at which seeding could plausibly operate.

Effects on Indigenous/Local Communities

Score: Negative

Confidence: Low

For Greenland and Arctic cloud seeding applications, Inuit and other indigenous communities could benefit from preserved glaciers, but are more likely to be negatively affected by altered precipitation patterns, disrupted weather systems, or changed water availability.

For Greenland and other Inuit homelands, any large-scale intervention would require the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and set out as a minimum standard of engagement in the Inuit Circumpolar Council's Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC has no formal position on geoengineering, but considers it to fall under its commitment

223 to Inuit self-determination, with the FPIC obligation extending to researchers as well as
224 to deployment (Crump, 2025).

225 Indigenous communities depend on predictable weather, water availability, and
226 ecosystem services that could be disrupted by any precipitation modification activities.
227 The negative rating reflects the more likely direction of effect; its magnitude remains
228 highly uncertain and community dependent.

229 **Ease of Reversibility**

230 **Score:** High **Confidence:** High

231 Cloud seeding is inherently transient. Once cloud seeding operations cease, the
232 atmospheric system returns to background conditions within hours to days. No
233 persistent chemical legacy remains at concentrations used in any plausible operation,
234 and no physical modification of the glaciological system would result.

235 Reversibility is genuinely easy, though this partly reflects that the intervention is unlikely
236 to produce any lasting effect in the first place. The **ease of reversibility** should not be
237 mistaken for a design virtue: it is substantially a consequence of the intervention's
238 negligible efficacy.

239 **Likelihood of Termination Shock**

240 **Score:** Low risk **Confidence:** High

241 There is no termination shock risk from cloud seeding. Unlike stratospheric aerosol
242 injection, cloud seeding produces no sustained atmospheric forcing that would be
243 unmasked upon cessation. The glaciological system would experience no abrupt
244 response to the end of operations.

245 The low termination shock risk is almost entirely attributable to the intervention's
246 negligible efficacy.

247 **Suitability within Current Legal/Governance Structures**

248 **Score:** Not possible **Confidence:** High

249 Antarctic cloud seeding or humidity augmentation operations would constitute
250 geoengineering activities subject to the Madrid Protocol and to the precautionary
251 approach towards all geoengineering activities in the Antarctic endorsed by the 2025
252 Antarctic Treaty Consultative Meeting (Siegert et al., 2025). Even operations
253 characterized as research would require a Comprehensive Environmental Evaluation
254 and Antarctic Treaty Consultative Party consensus, which the current governance
255 environment does not support.

For Greenland and the Arctic, national authorizations would be required, and transboundary precipitation effects could engage international atmospheric liability frameworks. Operations in Greenland would require authorization from the Greenland Government with FPIC obligations to Inuit (United Nations, 2007; ICC, 2022). In practice, governance obstacles are prohibitive at any scale approaching glaciological relevance.

Attention from the Public

Score: Low **Confidence:** Medium

Cloud seeding as a glaciological intervention receives minimal dedicated academic attention. It appears in broad geoengineering reviews (Lockley et al., 2020), but no peer-reviewed study has specifically examined cloud seeding for ice sheet stabilization; the only glacier application, a short trial on a small mountain glacier in China (Wang et al., 2020), was aimed at slowing local melt. Academic engagement remains limited. Media coverage is occasional and typically treats cloud seeding in agricultural rather than glaciological contexts. Commercial interest is absent.

Overall Assessment

Cloud seeding does not offer a credible pathway to meaningful glaciological intervention or sea level management.

The most basic obstacle is the atmospheric condition of the target areas. Antarctica is an extreme polar desert, and the moisture deficit is not a technological problem but a consequence of the large-scale atmospheric circulation of the polar cell. Cold, dry air descends over the Antarctic plateau, and the extreme cold limits how much water vapor the atmosphere can hold, preventing the accumulation of moisture needed for precipitation. No realistic moisture-introduction technology could alter this circulation pattern at the scales required. At coastal margins — where moisture availability is less limiting — the primary drivers of ice loss are oceanographic, not atmospheric.

For Greenland and Arctic mountain glaciers, the concept is marginally more atmospherically plausible — moisture is more abundant, and conventional cloud seeding has demonstrated modest effects in some mid-latitude contexts. But the glaciological relevance remains low: Greenland's mass loss is driven by surface melt and ocean-forced dynamic discharge, neither of which is addressed by modest precipitation enhancement, and mountain glaciers' total sea level contribution, while significant, cannot be meaningfully addressed through precipitation enhancement alone.

The two criteria where cloud seeding scores favorably — reversibility and termination shock — are favorable because the intervention is likely to do very little. Its

291 environmental risk is moderate, arising from silver iodide accumulation and precipitation
292 redistribution.

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Increasing Glacier Thickness by Artificial Snow Production

Artificial snowmaking involves mechanically producing snow — through snow guns, fan guns, or lance systems that pressurize water into cold air — and depositing it on glacier surfaces to increase surface mass balance and slow retreat. The technique is widely deployed in the ski industry and has been proposed specifically for glacier preservation by Oerlemans et al. (2017), whose feasibility study on Switzerland's Morteratsch Glacier remains the most rigorous published analysis. Ongoing experiments, notably the MortAlive project funded by the Swiss National Science Foundation, are testing next-generation approaches that aim to reduce dependence on external water and energy.

The fundamental assessment challenge is the same as for geotextile insulation: the technique demonstrably works at local scale but faces logistical, energetic, and economic barriers that prevent scaling beyond individual commercially managed glaciers. Huss (2024) concludes that technical approaches to reducing glacier melt work locally but 'clearly fail at the larger scale', with an effect 'at the scale of entire glaciers or mountain ranges' that is 'absolutely negligible'. Wang et al. (2025) include snowmaking within their review of mountain glacier geoengineering techniques, citing modelling of summer snowmaking on Morteratsch (Oerlemans et al., 2017) and a field trial on the Muz Taw Glacier, China, where artificially induced snowfall reduced mass loss by 14–17% over the trial period (Wang et al., 2020); they conclude that cost and **scalability** constraints limit broader application.

Outcome Reliability

Score: Low

Confidence: Medium

At the scale of individual glacier patches, artificial snowmaking reliably reduces ablation. At Austrian glacier ski resorts, mass balance management combining snow farming, grooming, and covers preserved up to 21 m of ice thickness over two decades (Fischer et al., 2016), and Wang et al. (2025) report melt reductions of 40–60% in field trials of surface interventions including artificial snow and geotextiles. Oerlemans et al. (2017) modeled that sustained snowmaking on Morteratsch could prevent 400–500 m of retreat over two decades. These local outcomes are well-established.

However, at the scales relevant to glacier preservation or sea level management, Outcome Reliability is low. Artificial snow has no mechanism to alter the energy balance processes driving ablation beyond the treated area and has no physical connection to the outlet glacier discharge processes — oceanic basal melt, calving — that dominate sea level contributions from Greenland and Antarctica. Huss et al. (2021) found that Switzerland's entire intervention program, covering approximately 0.18 km², reduces country-wide ice loss by approximately 0.03%, although this program relies mainly on

geotextile covers rather than snowmaking. A low score reflects this mismatch between demonstrated local efficacy and system-scale irrelevance.

Technological Readiness Level

Score: Medium

Confidence: Medium

TRL 4-6 for glacier preservation applications. Snowmaking technology is operationally mature at ski resorts (TRL 7-9), but for glacier conservation the relevant TRL reflects systems optimized for that purpose without commercial resort infrastructure. Conventional snow guns require 600-1,200 liters of water per minute, ambient temperatures below approximately -2 to -3 degrees C wet-bulb, and 15-60 kW of electrical power per gun — manageable at ski resorts but limiting at remote glacier sites. MortAlive represents the leading edge of adaptation for conservation use, testing approaches that do not draw on off-glacier energy or water sources. Results from this and similar projects over the coming years will advance the TRL.

Scalability

Score: Low

Confidence: Medium

Scaling is constrained by water and energy requirements that incremental technology improvements cannot address. Abermann et al. (2022) concluded that preserving an iconic Alpine glacier through such measures would be too expensive to justify, and glacier stabilization is therefore realistic only where commercial revenue can offset operating costs — a condition met by a small minority of glaciers globally. For comparison, Huss et al. (2021) estimated that covering the 1,000 largest Swiss glaciers with geotextiles over 76% of their surface would cost about CHF 1.4 billion per year, and that even complete coverage would have avoided only about two-thirds of average annual ice loss. The constraints are physical and economic, not solvable by improved equipment. **Scalability** is low.

Timeliness for Near-Future Effects

Score: Medium

Confidence: Medium

Snowmaking technology is operational today. Experiments on Morteratsch and similar sites will deliver clear feasibility results within several years. For specific commercially viable glaciers with suitable water and energy access, meaningful expansion is achievable within 20 years. The medium rating applies strictly to this narrow context. At scales relevant to sea level management, timeliness is effectively zero — the technology cannot be deployed at those scales within any realistic timeframe.

Potential to Make a Difference in the Arctic/Northern Regions

Score: Low

Confidence: High

Arctic glacier retreat is driven by sustained atmospheric warming that snowmaking cannot counteract. Many Arctic sites also experience extended periods of above-freezing temperatures that limit the snowmaking window, and the required infrastructure does not exist at most locations. The technique can preserve ice locally during individual winters but does not alter a glacier's long-term energy balance under a warming climate. Northern potential is low.

Potential to Make a Global Difference

Score: Low **Confidence:** High

Mountain glaciers are projected to contribute 90–154 mm of sea-level rise by 2100 (Rounce et al., 2023), and snowmaking cannot address the Greenland and Antarctic ice sheets that dominate long-term sea level risk. Even comprehensive deployment across accessible mountain glaciers — an impossibly expensive scenario — would not meaningfully alter sea level trajectories. Zekollari et al. (2025) project that about 54% of present-day glacier mass would remain at equilibrium under 1.5°C of warming but only about 24% under 2.7°C. This difference of roughly 30% of global glacier mass is far beyond anything snowmaking could approach. Global impact potential is negligible.

Cost to Benefit Comparison

Score: Prohibitive **Confidence:** High

At ski resort scale, economics are internally justified by commercial revenue. As a conservation or sea level management strategy, the cost-benefit ratio is prohibitive. Abermann et al. (2022) concluded that preserving an iconic Alpine glacier would be too expensive to justify. Even geotextile covering, which is cheaper than snowmaking, would cost over CHF 1 billion per year to apply to all Swiss glaciers while only slowing their decline (Huss et al., 2021). For the vast majority of glaciers lacking commercial value and remote infrastructure, costs are entirely unjustifiable. Prohibitive at scale.

Likelihood of Environmental Risks

Score: Some Risk **Confidence:** Medium

Environmental risks are real but bounded at current deployment scales. Key concerns:

Water consumption: snow guns consume hundreds of liters per minute, potentially competing with downstream agricultural and municipal needs in water-stressed alpine regions.

Chemical additives: some operations have used Snomax (*Pseudomonas syringae* derivatives) to improve ice nucleation at higher temperatures. Safety assessments generally find low risk, but regulatory status varies by jurisdiction (Lagriffoul et al., 2010).

Microclimate and drainage: artificial snow can alter local drainage patterns in ways not yet fully characterized, though effects at current scales are modest.

Effects on Indigenous/Local Communities

Score: Beneficial **Confidence:** Medium

In communities where glaciers hold commercial, cultural, or water-supply significance, snowmaking that preserves a valued glacier has direct community benefit. Alpine communities in Switzerland, Austria, and Italy have supported such interventions. The beneficial rating reflects genuine value in contexts where the technology is deployed, acknowledging this is a narrow set globally. For high-mountain Asian communities dependent on glacial meltwater, snowmaking is largely inapplicable at current technology levels due to remoteness and energy constraints.

Ease of Reversibility

Score: High **Confidence:** Medium

Equipment can be removed at season's end with no permanent landscape modification. However, a glacier maintained by snowmaking is artificially preserved inconsistently with the prevailing climate; cessation allows rapid return to the natural retreat trajectory, with accumulated snow melting within one to several seasons. Reversibility of infrastructure is easy; the glaciological state returns to its natural trajectory on short timescales. Reversibility is rated high because stopping snowmaking leaves nothing behind to undo: it has to keep running to have any effect.

Likelihood of Termination Shock

Score: Low Risk **Confidence:** Medium

Cessation of snowmaking produces no termination shock. The glacier returns to its natural ablation trajectory with no accumulated atmospheric forcing to be unmasked, no dynamic instability triggered, and no non-linear glaciological response. Low risk.

Suitability within Current Legal/Governance Structures

Score: Possible **Confidence:** Medium

Artificial snowmaking at ski resorts operates within existing commercial and environmental permitting frameworks across European countries, North America, and China. Water use permits and environmental assessments are standard requirements, but no special geoengineering governance is involved. MortAlive operates under standard Swiss research grant frameworks. At larger scales in protected natural areas or transboundary glacier systems, governance complexity increases, but for current deployment contexts the framework is supportive.

For Greenland and other Inuit homelands, any large-scale intervention would require the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and set out as a minimum standard of engagement in the Inuit Circumpolar Council's Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC has no formal position on geoengineering, but considers it to fall under its commitment to Inuit self-determination, with the FPIC obligation extending to researchers as well as to deployment (Crump, 2025).

Attention from the Public

Score: Medium

Confidence: Medium

Academic attention centers on Oerlemans et al. (2017) and subsequent work from MortAlive and Glaciers Alive projects, with critical scaling analyses by Huss et al. (2021), Abermann et al. (2022), Wang et al. (2025), and Huss (2024). Media attention is substantial, driven by high-profile Alpine glacier retreat stories. Commercial interest from the winter tourism industry is genuine and growing. Academic consensus has moved toward viewing snowmaking as a commercially motivated local preservation tool rather than a climate intervention. Medium rating reflects genuine engagement without progress toward climate-scale relevance.

Overall Assessment

Artificial snowmaking for glacier preservation occupies the same analytical position as geotextile insulation: a local, commercially viable, technically operational technique with negligible significance at glacier-system, regional, or global scales. Oerlemans et al. (2017), who proposed the concept, carefully framed it as a feasibility study for a single iconic glacier — not a strategy for sea level management.

The score pattern — high on governance, and community benefit; low on scalability, global potential, and cost-benefit at scale — mirrors that of other surface interventions. Both share the core limitation identified by Huss (2024): they preserve ice locally and commercially but cannot replace emissions reduction as the determinative factor in long-term glacier survival. Wang et al. (2025) reach the same conclusion: while melt reductions of 40-60% are achievable in field trials, these solutions are temporary and unsustainable at meaningful scale.

The appropriate application is as a commercially and culturally motivated preservation tool for specific valued glaciers where communities can finance sustained operations. It should not be presented as a contribution to sea level management or as an alternative to decarbonization. The ongoing MortAlive experiments are valuable for addressing the energy and water dependence constraints of conventional snowmaking, expanding the

470 range of glaciers where the technique is technically viable — even if broader climate
471 relevance remains limited.

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Glacier Albedo Increase

Glacier albedo increase aims to reduce surface melt by making the ice surface more reflective, so that it absorbs less shortwave radiation. Proposed approaches include spreading reflective particles — most prominently hollow glass microspheres, developed by the Ice911/Arctic Ice Project for sea ice (Field et al., 2018) — applying reflective foams or coatings, and removing dark impurities such as black carbon, dust, and rubble that lower surface albedo (Lockley et al., 2020; Zhang et al., 2021). Covering ice with geotextile fabrics, which raises surface reflectivity but also insulates the ice, is assessed separately (Assessment 4: Glacier Insulation with Fabrics).

Unlike fabric covers, particle-based albedo modification has no operational record on glaciers. The leading approach, glass microspheres, was developed for sea ice rather than glacier ice, and the Arctic Ice Project ended in January 2025, citing inconclusive ecotoxicological results, a difficult funding environment, and resistance to introducing new materials into the Arctic (Arctic Ice Project, 2025). Subsequent laboratory studies found that marine organisms ingest the microspheres, with sublethal effects on growth and energetics (Farkas et al., 2025; Hansen et al., 2026). Webster & Warren (2022) also found that the microspheres absorb enough sunlight to darken high-albedo surfaces, producing net warming rather than cooling (Siegert et al., 2025). Removing dark impurities can restore albedo locally, but has been proposed only conceptually and for small, accessible sites (Lockley et al., 2020).

The intervention is most mechanistically relevant in Greenland, where surface melt accounts for roughly half of present mass loss and dark particles concentrate at the surface during the melt season. Lockley et al. (2020) note, however, that Greenland's dark region is extensive, that spreading material by aircraft would be prohibitively costly over such areas, and that working only on the fast outlet glaciers offers no leverage because their flow is not controlled by surface melt. In Antarctica, where surface melt plays almost no role in mass loss, the intervention has essentially no application.

Outcome Reliability

Score: Low

Confidence: Medium

The underlying physics is straightforward: a brighter surface absorbs less shortwave radiation, and removing dark impurities restores baseline albedo locally. Albedo reduction from black carbon, dust, and microbial growth is an established driver of glacier melt (Zhang et al., 2021). However, no particle-based or coating approach has been shown to reduce melt on glaciers, and the evidence that does exist points the other way: Webster & Warren (2022) found that glass microspheres darken high-albedo surfaces, producing net warming.

At the scales relevant to glacier preservation or sea level management, Outcome Reliability is low. For Antarctica, surface melt plays essentially no role in mass loss — Antarctic ice loss is driven almost entirely by ocean-forced dynamic discharge (Lockley et al., 2020). For Greenland, surface melt accounts for approximately half of mass loss, but the expansive ablation zone far exceeds any plausible treatment area. Melt reduction in treated areas does not translate directly into glacier-scale mass-balance improvement, since glaciers are dynamic systems in which changes in surface melt affect ice dynamics, calving rates, and proglacial lake levels in ways not captured by surface energy balance alone. Wang et al. (2025) note limited understanding of the long-term impacts of surface interventions on glacier dynamics and mass balance.

Technological Readiness Level

Score: Low **Confidence:** Medium

Particle-based albedo modification for glaciers is at TRL 1–3. The most developed approach, glass microspheres, was designed for sea ice rather than glacier ice and has been effectively abandoned: the Arctic Ice Project ended in January 2025 with its ecotoxicological testing unresolved (Arctic Ice Project, 2025). No reflective particle, foam, or coating has been demonstrated on glaciers at any meaningful scale, and no engineering design exists for application over ice-sheet ablation zones.

Removing dark impurities is technically simple but has been proposed only conceptually and for small, accessible sites (Lockley et al., 2020). The low rating reflects the absence of any system validated in the intended environment.

Scalability

Score: Low **Confidence:** High

Aircraft spreading could, in principle, distribute reflective material over large areas, but Lockley et al. (2020) conclude this would be prohibitively costly when extended over the vast areas of Greenland. Ground-based application is constrained because glaciers are crevassed, remote, and hazardous for machinery and people (Lockley et al., 2020).

The quantities of material required are themselves prohibitive. Webster & Warren (2022) estimated that treating Arctic sea ice with glass beads would require approximately 360 megatons per year (comparable to annual global plastic production) with substantial emissions from manufacturing (Siegert et al., 2025). **Scalability** is low.

Timeliness for Near-Future Effects

Score: Low **Confidence:** High

No particle-based or coating approach is ready for deployment on glaciers, and the leading candidate has been abandoned. Developing and testing a new material for glacier application, establishing its environmental safety, securing permission, and deploying it over areas large enough to matter could not be completed within 20 years. Local removal of dark impurities could be implemented quickly, but only over areas far too small to make a significant difference.

Potential to Make a Difference in the Arctic/Northern Regions

Score: Low **Confidence:** Medium

In the Arctic and northern regions, surface melt processes are more significant relative to total mass loss than in Antarctica, making albedo and insulation interventions more mechanistically relevant. Greenland, Arctic mountain glaciers, and sub-Arctic glaciers all experience surface melt as a primary ablation mechanism. Zhang et al. (2021) established albedo reduction — from black carbon, dust, and microbial blooms — as a major driver of Tibetan glacier melt, and impurity-driven darkening likewise contributes to melt on Arctic glaciers and the Greenland ablation zone (Lockley et al., 2020).

However, Lockley et al. (2020) emphasize that in Greenland, 'the dark region is extensive,' and that surface albedo modifications would be 'extensive and costly,' while dynamic outlet losses — which dominate long-term sea level contribution — are not affected by surface albedo. The shorter ablation season and meteorological regime of northern regions (less intense solar radiation, a higher proportion of sensible heat flux) may further reduce effectiveness relative to mid-latitude settings. The low rating reflects these constraints of scale and the continued dominance of other processes in glacier mass loss.

Potential to Make a Global Difference

Score: Low **Confidence:** High

The largest potential contributions to long-term sea-level rise come from dynamic ice discharge from the Antarctic and Greenland ice sheets, driven by basal melt of ice shelves and grounding line retreat — neither of which is affected by surface albedo or insulation (Lockley et al., 2020). These interventions address the wrong process for the glaciers that matter most. For mountain glaciers, Rounce et al. (2023) project 26–41% mass loss by 2100 regardless; the difference between aggressive and moderate emissions reduction is of a magnitude these surface techniques cannot approach. Albedo modification addresses the wrong process for the ice masses that matter most.

Zekollari et al. (2025) project that about 54% of present-day glacier mass would remain at equilibrium under 1.5°C of warming but only about 24% under 2.7°C. This difference of roughly 30% of global glacier mass is far beyond anything an albedo program could

approach. Wang et al. (2025) conclude that 'these solutions are temporary and unsustainable,' and that long-term glacier conservation requires climate stabilization through decarbonization.

Cost to Benefit Comparison

Score: Prohibitive **Confidence:** Medium

No cost estimates exist for glacier-scale albedo modification. Lockley et al. (2020) judge aircraft spreading to be prohibitively costly over the vast areas of Greenland, and Siegert et al. (2025) consider the financial feasibility of deploying glass beads at scale questionable even for sea ice, given the costs of materials, manufacturing, and logistics.

Brown et al. (2021) project global sea-level damages of up to US\$22 trillions per year by 2100 without additional adaptation, but no albedo program approaches the scale needed to meaningfully affect this trajectory. Cost-benefit is prohibitive.

Likelihood of Environmental Risks

Score: Some risk **Confidence:** Low

Unlike fabric covers, which can be removed, dispersed albedo materials enter the environment directly. Key concerns:

Ecotoxicity: in laboratory exposures, cold-water copepods (*Calanus finmarchicus*), cod larvae, and benthic polychaetes (*Capitella* sp.) ingested hollow glass microspheres. Copepodites exposed for 17 days at 1–100 mg/L showed reduced lipid accumulation and survival, and higher concentrations caused mortality and developmental harm (Hansen et al., 2026); polychaetes showed reduced growth and development over 42 days, while blue mussels were largely unaffected (Farkas et al., 2025). The lowest concentration tested, 1 mg/L, is within the range modelled for a thin microsphere layer on sea ice (Hansen et al., 2026). Effects on fish larvae over longer periods remain unresolved.

Reversal of intended effect: microspheres can darken high-albedo surfaces and produce net warming (Webster & Warren, 2022).

Downstream transport: dispersed particles cannot be recovered and would enter meltwater and downstream freshwater and fjord systems. Hopwood et al. (2025) highlight that perturbations to glacial meltwater chemistry and volume can cascade through marine ecosystems in glacially fed fjords.

The "some risk" rating reflects impacts that would extend beyond the treated area into downstream ecosystems. At the scales needed to make a difference, these risks could approach the high-risk category.

Effects on Indigenous/Local Communities

Score: Neutral

Confidence: Low

For communities that depend on glacier meltwater — glaciers serve as seasonal water towers for nearly two billion people (Immerzeel et al., 2020) — interventions that delay glacier retreat could in principle extend meltwater availability. Against this, dispersed particles would enter the same meltwater that downstream communities use, and the Arctic Ice Project reported broad resistance to introducing new materials into the Arctic (Arctic Ice Project, 2025). For Greenland and other Inuit homelands, any large-scale intervention would require the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and set out as a minimum standard of engagement in the Inuit Circumpolar Council's Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC has no formal position on geoengineering, but considers it to fall under its commitment to Inuit self-determination, with the FPIC obligation extending to researchers as well as to deployment (Crump, 2025).

The neutral rating reflects a balance between potential benefits and harms, with significant variation by location, scale, and community context.

Ease of Reversibility

Score: High

Confidence: Medium

Albedo effects are transient: once application stops, the surface returns to its pre-intervention albedo, and the glacier resumes its natural ablation trajectory. No persistent physical modification of the glacier is made.

The main caveat is that, unlike fabric covers, dispersed particles cannot be retrieved. The material persists in meltwater, sediments, and downstream ecosystems, and those effects are not reversible in the same sense as the albedo change itself.

Likelihood of Termination Shock

Score: Low Risk

Confidence: High

There is no meaningful termination shock risk from albedo modification. Ceasing application returns the surface to its pre-intervention albedo, and the glacier resumes its natural ablation rate without abrupt acceleration. There is no equivalent to stratospheric aerosol injection termination shock: no accumulated greenhouse gas forcing is unmasked, and no large-scale atmospheric or ocean dynamics are disturbed (cf. Lockley et al., 2022, for termination risks of solar geoengineering). Ice preserved during the intervention period remains, and glaciers return gradually to their pre-intervention

647 ablation trajectory with no system-level rebound, masked forcing, or critical threshold
648 crossing.

649 Suitability within Current Legal/Governance Structures

650 **Score:** Challenging **Confidence:** Medium

651 Small-scale removal of dark material from accessible mountain glaciers in national
652 jurisdiction would fall within existing permitting frameworks. Dispersing engineered
653 particles is different in kind: it amounts to deliberately introducing material into the
654 environment, which would require environmental assessment and, for Greenland and
655 other Arctic applications, FPIC processes with Inuit (United Nations, 2007; ICC, 2022).

656 Siegert et al. (2025) note that particle-based albedo approaches may cross governance
657 boundaries, since material is transported by meltwater and ocean currents.

658 Transboundary glacier systems in the Himalaya, Karakoram, and Andes feed shared
659 river systems where unilateral interventions could create disputes. The "challenging"
660 rating reflects these obstacles for any deployment approaching climate relevance.

661 **Attention from the Public**

662 **Score:** Low **Confidence:** High

663 Albedo modification for glaciers specifically receives little dedicated attention. The glass
664 microsphere concept attracted considerable media attention for sea ice, but the Arctic
665 Ice Project ended in January 2025 (Arctic Ice Project, 2025), and recent comprehensive
666 assessments are critical of the approach (Siegert et al., 2025). Removal of dark
667 impurities is discussed conceptually (Lockley et al., 2020), and the role of impurities in
668 glacier darkening is well studied (Zhang et al., 2021), but no research programme or
669 commercial effort is developing albedo enhancement for glacier preservation. The low
670 rating reflects an approach whose leading candidate has been abandoned.

671 **Overall Assessment**

672 Glacier albedo increase rests on sound physics — a brighter surface absorbs less
673 sunlight — but, unlike fabric covers (Assessment 4), it has no demonstrated record of
674 reducing melt on glaciers. Its most developed form, glass microspheres, has been
675 discontinued, with laboratory studies showing sublethal effects on key marine
676 organisms (Farkas et al., 2025; Hansen et al., 2026) and evidence that the material can
677 warm rather than cool bright surfaces.

678 The intervention also exhibits a triple mismatch with what sea-level management
679 requires. First, a mechanism mismatch: the dominant driver of worst-case sea-level rise
680 is ocean-forced dynamic discharge from Antarctic and Greenland outlet glaciers, which
681 surface albedo does not affect (Lockley et al., 2020). Second, a scale mismatch:

Greenland's dark region is extensive, aircraft application would be prohibitively costly, and the material quantities estimated for comparable sea-ice applications approach annual global plastic production (Siegert et al., 2025). Third, a permanence mismatch: albedo gains last only while the surface is treated, while dispersed material persists in downstream ecosystems after the benefit has ended.

Greenland is where the mechanism is most relevant, since surface melt drives roughly half of its mass loss. But the area involved, the cost of reaching it, and the lack of leverage on the fast outlet glaciers (Lockley et al., 2020) make meaningful deployment implausible. In Antarctica the intervention has no meaningful application.

The role for albedo intervention is narrow: removing dark impurities from small, accessible glaciers of particular cultural or ecological value may be locally effective (Lockley et al., 2020). Albedo modification will not have an impact on reducing sea level rise.

Glacier Insulation with Fabrics and Geotextiles

Glacier insulation involves covering ice with geotextile fabrics - typically non-woven polypropylene fleece, HDPE fabrics, or aluminized sheets - to reduce surface melt. Covers act in two ways: their high reflectivity reduces absorbed shortwave radiation, and they form an insulating barrier that suppresses turbulent heat fluxes and melt-pond formation (Fischer et al., 2016). Albedo modification without a cover — reflective particles, coatings, or removal of dark impurities — is assessed separately (Assessment 3: Glacier Albedo Increase).

Covering glaciers with fabric has the longest real-world record of any glacier geoengineering approach. Commercial deployments have operated at ski resorts in the Alps since the early 2000s, with field trials consistently showing reductions in ablation of 40–90% in covered areas, and approximately 350,000 m³ of ice preserved annually across approximately 0.18 km² of Swiss glaciers (Huss et al., 2021; Wang et al., 2025). The central question is not whether the technique works locally — it demonstrably does — but whether it can be deployed at scales relevant to sea level rise or meaningful glacier preservation.

Applicability to the ice sheets is limited. In Antarctica, surface melt plays essentially no role in mass loss (Lockley et al., 2020). In Greenland, surface melt accounts for about half of mass loss, but the ablation zone spans approximately 300,000 km², and covers can be delivered only to glaciers accessible from existing transport networks (Wang et al., 2025), a condition that excludes almost all of the Greenland ablation zone.

Outcome Reliability

Score: Low **Confidence:** High

At the local scale of tens to hundreds of square meters, geotextile covers reliably reduce ice ablation by 40–90%. These outcomes are well established by multiple independent field studies across Austria, Italy, Switzerland, China, and Armenia (Olefs & Lehning, 2010; Nestler et al., 2014; Senese et al., 2020; Liu et al., 2022; Xie et al., 2024).

However, at the scales relevant to glacier preservation or sea level management, Outcome Reliability is low. For Antarctica, surface melt plays essentially no role in mass loss — Antarctic ice loss is driven almost entirely by ocean-forced dynamic discharge (Lockley et al., 2020). For Greenland, surface melt accounts for approximately half of mass loss, but the ablation zone spans approximately 300,000 km², far exceeding any plausible treatment area. Melt reduction in treated areas does not translate directly into glacier-scale mass-balance improvement, since glaciers are dynamic systems in which changes in surface melt affect ice dynamics, calving rates, and proglacial lake levels in ways not captured by surface energy balance alone. Wang et al. (2025) note limited

733 understanding of the long-term impacts of surface interventions on glacier dynamics
734 and mass balance. Huss (2024) concludes that while local covering works, its effect at
735 the scale of entire glaciers is negligible.

736 **Technological Readiness Level**

737 **Score:** Medium **Confidence:** High

738 Geotextile glacier protection is genuinely mature at small scale. Commercial
739 deployments have operated at multiple Alpine sites for over 20 years. Fischer et al.
740 (2016) documented over a decade of mass balance management at Austrian glacier ski
741 resorts, showing up to 21 m of ice thickness preserved in managed areas. Materials —
742 non-woven polypropylene fleece, HDPE fabrics, aluminized sheets — are commercially
743 available and have been applied to approximately 0.18 km² of Swiss glaciers with
744 measurable results (Huss et al., 2021).

745 The medium TRL rating reflects this genuine operational history, constrained by the
746 scale at which the technology has actually been demonstrated. Deployment at glacier-
747 wide or ice-sheet scales — requiring hundreds of thousands to millions of km² for
748 meaningful impact — has not been attempted or technically designed for.

749 **Scalability**

750 **Score:** Low **Confidence:** High

751 The gap between proven performance and required scale is the defining limitation of
752 fabric covers as a climate strategy. Currently, approximately 0.18 km² of Swiss glaciers
753 are covered — about 0.02% of Switzerland's total glacier area (Huss et al., 2021). Huss
754 et al. (2021) estimated that covering the 1,000 largest Swiss glaciers over 76% of their
755 surface would cost about CHF 1.4 billion per year, and that even complete coverage
756 would have avoided only about two-thirds of average annual ice loss; the current
757 program mitigates about 0.03% of Swiss ice loss.

758 Wang et al. (2025) note that geotextiles can only be delivered to glaciers that are easily
759 accessible via existing transportation networks, excluding most glaciers relevant to
760 regional water security and nearly all of the Greenland ablation zone. Geotextiles also
761 age and degrade, requiring regular replacement, which adds further logistical and
762 financial constraints. Wang et al. (2025) and Huss (2024) both conclude that cost
763 prevents large-scale application. **Scalability** is low.

764 **Timeliness for Near-Future Effects**

765 **Score:** Medium **Confidence:** Medium

766 At the scale where geotextiles are already deployed, effects are immediate — covers
767 deployed in spring show measurable ablation reduction within the same summer

season, making this one of the fastest-acting interventions conceivable. For specific commercially viable glaciers near existing infrastructure, meaningful expansion is achievable within 20 years, and locally detectable differences are already happening.

The timeliness rating is medium rather than high because the intervention cannot produce effects at the scale needed for sea level management within 20 years or any realistic timeframe. The distinction between local and systemic timeliness is critical: at the scale of meaningful glacier preservation or regional hydrology, no amount of accelerated deployment can overcome the cost and logistical constraints that make large-scale deployment implausible.

Potential to Make a Difference in the Arctic/Northern Regions

Score: Low **Confidence:** Medium

In the Arctic and northern regions, surface melt is more significant relative to total mass loss than in Antarctica, making surface insulation more mechanistically relevant. Greenland, Arctic mountain glaciers, and sub-Arctic glaciers all experience surface melt as a primary ablation mechanism.

However, the Greenland ablation zone is vast and largely inaccessible, and Lockley et al. (2020) note that any surface modification there would be extensive and costly, while dynamic outlet losses, which dominate sea level contribution, are unaffected by surface treatments. The shorter ablation season and meteorological regime of northern regions (less intense solar radiation, a higher proportion of sensible heat flux) may also change the relative effectiveness of covers compared with mid-latitude Alpine deployments. The low rating reflects constraints of scale and the continued dominance of other processes in glacier mass loss.

Potential to Make a Global Difference

Score: Low **Confidence:** High

The largest potential contributions to long-term sea-level rise come from dynamic ice discharge from the Antarctic and Greenland ice sheets, driven by basal melt of ice shelves and grounding-line retreat — neither of which is affected by surface insulation (Lockley et al., 2020). For mountain glaciers, Rounce et al. (2023) project 26–41% mass loss by 2100 regardless; the difference between aggressive and moderate emissions reduction is of a magnitude these surface techniques cannot approach.

Zekollari et al. (2025) project that about 54% of present-day glacier mass would remain at equilibrium under 1.5°C of warming but only about 24% under 2.7°C — a difference of roughly 30% of global glacier mass, far beyond anything a fabric-covering program could approach. Wang et al. (2025) conclude that such surface solutions are temporary and unsustainable, and that long-term glacier conservation requires climate stabilization

through decarbonization. Huss (2024) also notes that curbing emissions is what decides between near-complete loss of Alpine glaciers and a considerable glacier area surviving. Global impact potential is negligible.

Cost to Benefit Comparison

Score: Prohibitive **Confidence:** High

At the local scale of ski resorts and tourist glaciers, economics are internally justified by commercial revenue. As a conservation or sea level management strategy, the cost-benefit ratio is prohibitive by orders of magnitude. Huss et al. (2021) estimated that current covering costs CHF 0.60–7.90 per cubic meter of ice preserved per year, depending on cover type and location, and that covering the 1,000 largest Swiss glaciers would cost about CHF 1.4 billion per year while only slowing their decline.

Wang et al. (2025) cite 'high costs associated with their use, including both labor for installation and the materials required for coverage' as a significant financial barrier even at current scales. Annual replacement generates significant waste requiring transport and responsible disposal. Brown et al. (2021) project global sea-flood damages of up to about US\$22 trillion per year by 2100 without additional adaptation, but no fabric program approaches the scale needed to meaningfully affect this trajectory. Huss (2024) and Wang et al. (2025) agree that costs are justified only in 'specific economic contexts' (tourism), not as a climate intervention.

Likelihood of Environmental Risks

Score: Some Risk **Confidence:** Medium

Environmental risks are real but bounded at current deployment scales. Key concerns include:

Microplastic contamination: polypropylene covers shed microplastic fibers, which accumulate on the ice surface (up to 3 km of fiber length per m² of ice) and are carried by meltwater and wind into downstream aquatic ecosystems, where they attach to or become embedded in invertebrates (Sattler et al., 2025).

Ecosystem disturbance: suppression of glacial cryoconite microbial communities in covered areas, and altered meltwater timing and volume affecting aquatic habitats. Hopwood et al. (2025) highlight that perturbations to glacial meltwater chemistry and volume can cascade through marine ecosystems in glacially fed fjords.

Declining performance: geotextiles degrade, tear, and become dirty, so that after a few years they 'no longer have any helpful effect' (Huss, 2024); operators typically replace them every three to eight years (Huss et al., 2021), increasing waste.

838 The "some risk" rating reflects genuine but largely localized, non-catastrophic, and
839 largely reversible risks at current scales.

840 **Effects on Indigenous/Local Communities**

841 **Score:** Neutral **Confidence:** Low

842 Fabric covers are among the most directly community-relevant interventions in this
843 series, operating on glaciers that local and Indigenous communities depend on for water
844 supply, cultural identity, and livelihoods. Potential positive effects include preservation of
845 downstream water supply — glaciers serve as seasonal water towers for nearly two
846 billion people (Immerzeel et al., 2020) — and maintenance of tourism and skiing
847 revenue in Alpine communities. For high-altitude glacier communities in Asia and South
848 America, interventions that delay glacier retreat could extend meltwater availability.

849 Negative effects include the visual impact of fabric arrays on culturally significant
850 glaciers, microplastic contamination of meltwater, and disruption of glacial ecosystems.
851 For Greenland and other Inuit homelands, any large-scale intervention would require
852 the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN
853 Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and
854 set out as a minimum standard of engagement in the Inuit Circumpolar Council's
855 Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC
856 has no formal position on geoengineering, but considers it to fall under its commitment
857 to Inuit self-determination, with the FPIC obligation extending to researchers as well as
858 to deployment (Crump, 2025). The neutral rating reflects a balance between potential
859 benefits and harms, with significant variation by location, scale, and community context.

860 **Ease of Reversibility**

861 **Score:** High **Confidence:** High

862 Fabric covers are among the most easily reversible in this assessment series. Covers
863 can be removed at the end of any season, no persistent physical modification of the
864 glacier is made, and the glacier returns to its natural trajectory upon removal. The
865 intervention is seasonal by design, and ski-resort operators routinely deploy and recover
866 fabrics each year.

867 The main caveat is that material waste from degraded fabrics constitutes a persistent
868 environmental legacy in the form of microplastic contamination, and that once covers
869 are removed the glacier ablates at its natural rate with no lasting benefit. High
870 reversibility is a genuine strength of this intervention class — it stands in stark contrast
871 to structural interventions (seabed curtains, buttressing) that are essentially irreversible
872 once deployed. Material disposal is the primary challenge upon decommissioning, and
873 established recycling pathways exist for most geotextile materials.

874 **Likelihood of Termination Shock**

875 **Score:** Low Risk **Confidence:** High

876 There is no meaningful termination shock risk from fabric covers. Removing covers
877 returns the surface to its natural state, and the glacier resumes its natural ablation rate
878 immediately and without abrupt acceleration. There is no equivalent to stratospheric
879 aerosol injection termination shock: no accumulated greenhouse gas forcing is
880 unmasked, and no large-scale atmospheric or ocean dynamics are disturbed (cf.
881 Lockley et al., 2022, for termination risks of solar geoengineering). Ice preserved during
882 the intervention period remains, and glaciers return gradually to their pre-intervention
883 ablation trajectory with no system-level rebound, masked forcing, or critical threshold
884 crossing. This is one of the few dimensions on which surface-based interventions score
885 strongly.

886 **Suitability within Current Legal/Governance Structures**

887 **Score:** Challenging **Confidence:** Medium

888 At current deployment scales — Alpine ski resorts and accessible mountain glaciers in
889 national jurisdiction — geotextile protection operates within existing commercial and
890 environmental permitting frameworks, with no special geoengineering governance
891 required. It operates outside the Antarctic Treaty System, in national or private land
892 jurisdictions where small-scale commercial deployment is already legal and practised.

893 Governance complexity increases markedly with scale: covering culturally or
894 ecologically significant glaciers in protected areas requires environmental permits;
895 transboundary glacier systems in the Himalaya, Karakoram, and Andes feed shared
896 river systems where unilateral interventions could create disputes; Indigenous rights
897 require FPIC processes (United Nations, 2007; ICC, 2022); and microplastic
898 contamination could generate environmental liability claims. The "challenging" rating
899 reflects the governance landscape for deployment approaching climate relevance, while
900 acknowledging that existing small-scale deployment is often legally permissible.

901 **Attention from the Public**

902 **Score:** Medium **Confidence:** Medium

903 Fabric insulation receive moderate academic attention, consistent popular media
904 coverage (geotextile photos from Swiss glaciers are among the most widely reproduced
905 images of glacier loss), and genuine commercial engagement from the ski industry. The
906 peer-reviewed literature is substantive, with high-quality field studies from Austria (Olefs
907 & Lehning, 2010), Italy (Senese et al., 2020), Switzerland (Fischer et al., 2016; Huss et
908 al., 2021), China (Liu et al., 2022; Xie et al., 2024), and Armenia, where covers were

applied to wind-blown snow accumulations rather than glacier ice to support water supply (Nestler et al., 2014).

Wang et al. (2025) provide the most comprehensive recent review. However, the community of researchers working on fabric covers as a glacier conservation strategy is small, and the most authoritative recent assessments (Huss, 2024; Wang et al., 2025) characterize them as locally viable but globally negligible. Commercial interest is confined to the ski industry.

Overall Assessment

Glacier insulation with fabrics is among the few interventions in this series with a peer-reviewed evidence base of demonstrated effectiveness at the point of deployment. Geotextile covers reliably reduce local ablation by 40–90% in covered areas, documented across multiple continents and two decades of field use. The local technology works.

The assessment is nonetheless pessimistic, for reasons independent of local effectiveness. The intervention exhibits a triple mismatch with what sea-level management requires. First, a mechanism mismatch: the dominant driver of worst-case sea-level rise is ocean-forced dynamic discharge from Antarctic and Greenland outlet glaciers, which surface insulation does not affect (Lockley et al., 2020). Second, a scale mismatch: the area over which fabric covers have been demonstrated — approximately 0.18 km² — is negligible against the area of glaciers relevant to sea level, and covering the 1,000 largest Swiss glaciers alone would cost about CHF 1.4 billion per year (Huss et al., 2021). Third, a permanence mismatch: covers preserve ice only while deployed; once removed, the glacier ablates at its natural rate with no lasting change in trajectory.

For Greenland, the mechanism is relevant — surface melt drives roughly half of mass loss — but the ablation zone is vast and almost entirely beyond the reach of the transport networks that cover deployment depends on. In Antarctica the intervention has no meaningful application.

Huss (2024) concludes that local covering works commercially but that its effect at the scale of entire glaciers or mountain ranges is negligible. The appropriate role for fabric covers is narrow but real: commercial asset protection at tourist sites and ski resorts, and potentially targeted preservation of culturally or ecologically significant small glaciers where local communities can sustain operations. Fabric covers will not mitigate against sea level rise.

Artificial Glaciers

Artificial glaciers are small-scale engineered ice masses created by directing winter meltwater or stream flow onto shaded mountain slopes or into constructed channels where it freezes, forming an ice body that melts more gradually through the spring and summer growing season than natural snowpack. The technique provides a form of coldwater storage that extends irrigation and drinking water availability into the dry, warm season in communities where natural glacier retreat has shortened or reduced the meltwater pulse on which agriculture depends.

The concept was pioneered at scale by retired civil engineer Chewang Norphel in Ladakh, India, who constructed over a dozen horizontal artificial ice fields between 1987 and the early 2000s using stone check dams and gravity-fed irrigation channels (Clouse, 2016; Nüsser et al., 2019). A more recent variant — the 'ice stupa' — was developed by Ladakhi engineer Sonam Wangchuk, using a pressurized buried pipe to create a tall conical ice structure that melts more slowly due to its geometry; pilot structures have been tested in Ladakh and Switzerland (Oerlemans et al., 2021; Balasubramanian et al., 2022). Nüsser et al. (2019) caution that the term is misleading: these seasonal ice reservoirs can in no way replace natural glaciers.

Artificial glaciers are best understood as a local climate adaptation tool rather than a glaciological or sea level intervention. They address a real and growing problem — the shifting timing of meltwater availability as glaciers thin and retreat (Immerzeel et al., 2020; Rounce et al., 2023) — but do so at scales of tens of farms and volumes of millions of liters, not at the scales of regional hydrology, glacier mass balance, or sea level management. This assessment evaluates the technique against the standard criteria used across this series, noting where the mismatch between the intervention's scale and the framework's climate-level ambitions produces ratings that may not reflect local utility.

Outcome Reliability

Score: Low **Confidence:** High

Artificial glaciers reliably achieve their primary local goal — storing winter meltwater as ice that releases gradually through the growing season — in the specific contexts where they have been deployed. This outcome is physically straightforward and supported by field experience (Nüsser et al., 2019; Clouse, 2016), although effectiveness varies from year to year with climatic conditions and is limited by natural hazards such as floods, landslides, and avalanches (Nüsser et al., 2019). Chewang Norphel has constructed over a dozen structures in Ladakh, demonstrating the concept works at village scale, and the ice stupa variant's reduced surface-area-to-volume ratio demonstrably slows melt relative to flat ice fields (Balasubramanian et al., 2022), although field

measurements show that more than three-quarters of the water sprayed onto ice stupas can be lost as runoff rather than stored as ice (Balasubramanian et al., 2022).

However, the intervention's relevance to sea level management, glacier preservation, or broader cryospheric objectives is negligible. The intervention is generally designed to provide water during the dry season with no annual net effect on sea level. The ice volumes created are many orders of magnitude smaller than the natural glacier losses they nominally address: Himalayan glaciers currently losing mass represent storage volumes billions of times larger than any conceivable artificial replacement (Rounce et al., 2023). Outcome Reliability for water storage at community scale is high within suitable environments. Outcome Reliability for any contribution to glacier mass balance, sea level management, or cryosphere conservation is nil. The low score reflects this fundamental mismatch between what the technology achieves and what this assessment framework evaluates.

Technological Readiness Level

Score: Medium

Confidence: Medium

TRL 5-7, within local context only. Artificial glacier construction requires no advanced technology: gravity-fed or pipe-pressurized water distribution, natural freezing, and site selection for shade and drainage are the essential elements. Norphel's ice fields are constructed from stone check dams and traditional irrigation channels (Clouse, 2016). The ice stupa system uses a single buried pipe with a nozzle; water pressure drives a fountain that freezes into a conical structure. Both approaches have been demonstrated at community scale in Ladakh, and the ice stupa concept has been piloted in Switzerland (Oerlemans et al., 2021; Balasubramanian et al., 2022) and tested in other high-mountain contexts.

The technology is operationally mature for its specific application. However, it has never been attempted at scales relevant to regional hydrology or climate, and no engineering designs for larger-scale deployment exist. TRL ratings above 7 would require demonstration in a range of geographic and climatic contexts at scales approaching regional significance, which has not been attempted.

Scalability

Score: Low

Confidence: High

Artificial glacier construction is inherently site-specific and small-scale. The physical constraints are stringent: suitable terrain (shaded, north-facing slopes with available water sources and drainage), cold winter temperatures, and the energy of the water supply all limit how much ice can be created. Notably, liquid water at large quantity would need to be available during the cold season. Nüsser et al. (2019) estimated that

one Ladakh ice reservoir stores 1,010–3,220 m³ of water, and published estimates for others range up to about 23,500 m³ — sufficient for a village but negligible against regional hydrological deficits (Nusser et al., 2019).

Unlike natural glaciers, which accumulate ice over decades or centuries in response to mass balance conditions, artificial glaciers must be remade each winter and survive only through one melt season and thus have no net sea level effect. At the landscape scale, artificial glaciers cannot compensate for the loss of natural glacier storage. Global glacier loss currently contributes approximately 0.7 mm per year to sea level rise (Hugonnet et al., 2021), driven by sustained atmospheric warming that artificial ice structures cannot counteract. As warming accelerates, the winter cold periods required for artificial glacier formation become shorter and less reliable, making the technique increasingly difficult to maintain even at its current scale (Clouse, 2016). **Scalability** is low.

Timeliness for Near-Future Effects

Score: High **Confidence:** Medium

Artificial glaciers can be constructed within a single winter season using locally available materials and labor. Effects — specifically, extended meltwater availability through the growing season — are apparent the following spring. No regulatory approval, engineering prototype, or extended research program is required at current scales. For communities in Ladakh, Nepal, and similar high-mountain regions where this technique is applicable, the 20-year timeliness assessment is high: the technology is ready now, and communities can benefit immediately.

The high rating reflects how quickly the technique delivers local water-supply benefits, and does not imply any significance at regional hydrological or climate scales, where the technique cannot achieve meaningful impact regardless of when it is deployed.

Potential to Make a Difference in the Arctic/Northern Regions

Score: Low **Confidence:** High

Artificial glaciers are most applicable in high-altitude arid mountain environments of Asia (Ladakh, Spiti, Hindu Kush, Karakoram foothills) and potentially South America (Andean communities facing similar water timing challenges). Arctic and sub-Arctic regions generally have sufficient natural snowpack and precipitation that the seasonal water deficit problem driving artificial glacier construction does not arise in the same form.

Moreover, Arctic communities are primarily affected by permafrost thaw, sea ice loss, and ocean-driven changes rather than the specific dry-season agricultural water deficit that artificial glaciers address. The technique offers no benefit to Arctic cryosphere

1053 preservation and no reduction in sea level rise from Arctic and Greenland ice loss. Arctic
1054 potential is low.

1055 **Potential to Make a Global Difference**

1056 **Score:** Low **Confidence:** High

1057 Artificial glaciers have no pathway to global significance. They are a village-scale water
1058 management technique applicable only in very specific arid mountain environments.
1059 Their total ice storage capacity across all plausible deployment sites would be
1060 measured in millions of cubic meters — negligible against global glacier losses of
1061 roughly 270 billion tonnes of ice per year (Hugonnet et al., 2021), with 26–41% of global
1062 glacier mass projected to be lost by 2100 (Rounce et al., 2023), and entirely irrelevant
1063 to sea level projections dominated by ice sheet dynamics.

1064 Natural glaciers are lost through sustained atmospheric warming, which artificial ice
1065 structures cannot counteract. As warming accelerates, the technique becomes
1066 increasingly difficult to maintain even at its current scale. Artificial glaciers may actually
1067 become less viable over time as warming continues, representing a shrinking rather
1068 than expanding opportunity.

1069 **Cost to Benefit Comparison**

1070 **Score:** Cost Effective **Confidence:** Medium

1071 In the specific communities where artificial glaciers address a genuine water security
1072 problem, the cost-benefit comparison is genuinely favorable. Norphel's Ladakh
1073 structures cost in the range of USD 4,000–10,000 each (about USD \$4,600–\$15,300 in
1074 2018), using local labor and traditional techniques, and provide water for irrigation
1075 during the growing season (Nüsser et al., 2019). The ice stupa model has attracted
1076 modest international funding and NGO support. Compared to alternative water
1077 infrastructure — dams, pipelines, desalination — artificial glaciers are extremely cost-
1078 effective at village scale.

1079 The cost-effective rating applies strictly to this narrow local use case. At any scale
1080 beyond individual communities, the economics deteriorate rapidly due to terrain
1081 constraints and the fundamental inability to scale the water source. Nüsser et al. (2019)
1082 note that the ratio of subsidies to effectiveness is a key consideration in evaluating
1083 these structures.

1084 **Likelihood of Environmental Risks**

1085 **Score:** Low Risk **Confidence:** Medium

1086 Environmental risks from artificial glacier construction are minimal. The technique uses
1087 natural water from local streams or meltwater, natural freezing, and minimal engineered

1088 structures. No foreign materials, chemicals, or substantial ground disturbance are
1089 involved. Local stream flow timing may be slightly modified by water diversion for ice
1090 formation, but volumes are small relative to natural flows. There is some risk of localized
1091 soil disturbance at the ice formation site and transient melt pond formation during the
1092 ablation season, but these effects are minor and reversible. The ecological footprint of
1093 this intervention is among the lowest of any considered in this assessment series.

1094 **Effects on Indigenous/Local Communities**

1095 **Score:** Beneficial **Confidence:** Medium

1096 Artificial glaciers are specifically designed and built to benefit local farming communities
1097 in water-stressed high-mountain environments. Communities in Ladakh where Norphel
1098 pioneered the technique have directly benefited from extended irrigation seasons,
1099 reduced crop failure risk, and greater food security (Clouse, 2016; Nüsser et al., 2019).
1100 The ice stupa model generated international media attention and NGO support that
1101 brought additional economic benefits to pilot communities.

1102 Unlike most other interventions in this assessment series, artificial glacier construction
1103 involves and benefits local communities directly, uses local knowledge and labor, and
1104 has few documented adverse social effects, although Nüsser et al. (2019) found that
1105 limited integration into the local socioeconomic setting — including a lack of funds for
1106 maintenance and competing demands on villagers' labour — reduces the benefits, and
1107 that many structures are frequently dysfunctional after floods. Community involvement
1108 and buy-in are integral to the technique's success, and the participatory nature of the
1109 intervention represents a model for locally-led climate adaptation. The technique is
1110 community-initiated, community-built, and community-maintained — a genuinely
1111 bottom-up approach to glacier-dependent water security.

1112 **Ease of Reversibility**

1113 **Score:** High **Confidence:** High

1114 Artificial glaciers are entirely reversible. They are constructed each winter and melt
1115 naturally each summer. If a community chose to stop constructing an artificial glacier,
1116 the only consequence would be the loss of the extended meltwater benefit the following
1117 season. Apart from small supporting structures such as stone check dams, channels, or
1118 buried pipes, no permanent structures, chemical additions, or landscape changes
1119 persist. Reversibility is as complete as any human activity could be.

1120 **Likelihood of Termination Shock**

1121 **Score:** Low **Risk Confidence:** High

1122 Cessation of artificial glacier construction produces no termination shock. Communities
1123 would return to the natural hydrological regime that existed before the technique was
1124 introduced. There is no masked forcing, no accelerated process, and no system-level
1125 rebound effect of any kind. The intervention creates no new dependencies beyond the
1126 meltwater benefit it provides, which was absent before deployment. However, continued
1127 warming could lead to a state of even less water security than pre-deployment
1128 conditions.

1129 **Suitability within Current Legal/Governance Structures**

1130 **Score:** Possible **Confidence:** High

1131 Artificial glacier construction operates at village scale, on community land, using
1132 traditional techniques. It requires no national regulatory approval, no formal
1133 environmental assessment at scales requiring government review, and no international
1134 governance process. The technique is already practiced legally in India and has been
1135 piloted in Switzerland without regulatory barriers (Oerlemans et al., 2021). As a
1136 community-level water management adaptation measure, it fits comfortably within
1137 existing local and national governance structures in the relevant countries. Legal and
1138 governance suitability is high.

1139 **Attention from Public**

1140 **Score:** Medium **Confidence:** Medium

1141 Artificial glaciers have attracted meaningful popular media attention, particularly the ice
1142 stupa model — the 2016 Rolex Laureate award to Sonam Wangchuk brought
1143 international profile. Academic interest is genuine but limited, with a small number of
1144 field studies from Ladakh and adjacent regions (Nüsser et al., 2019; Clouse, 2016;
1145 Oerlemans et al., 2021; Balasubramanian et al., 2022). Immerzeel et al. (2020) provide
1146 important wider context on mountain water tower vulnerability that frames the
1147 adaptation challenge artificial glaciers partially address.

1148 Commercial interest is essentially nil — the technique is a community adaptation tool,
1149 not a commercial product. Academic engagement focuses on field evaluation, and
1150 community impacts rather than scaling or climate significance. The medium rating
1151 reflects genuine but bounded attention appropriate to the technique's limited scope.

1152 **Overall Assessment**

1153 Artificial glaciers are a genuinely useful adaptation tool for a specific and well-defined
1154 problem: extending seasonal meltwater availability in arid high-mountain communities
1155 facing glacier retreat. At this scale, the technology is mature, cost-effective,
1156 environmentally benign, and community-beneficial. It is well suited as a development
1157 and adaptation measure in the communities where it is applicable.

As a glaciological or climate intervention — aimed at sea level management, ice sheet stabilization, or meaningful contributions to cryosphere conservation — it has no credible role. The volumes of ice that can be artificially created are many orders of magnitude smaller than natural glacier ice losses (Rounce et al., 2023); the technique cannot counteract atmospheric warming; and it has no relevance to the dominant mechanisms of sea level rise from ice sheets (Rounce et al., 2023).

The pattern of scores for this intervention is instructive: it scores very poorly on criteria relevant to climate-scale impact (scalability, global potential, Arctic potential) and very well on criteria relevant to local community application (reversibility, community impact, governance, cost-benefit). This confirms that the intervention is well-matched to its actual role — local adaptation — and poorly matched to the framing of glaciological geoengineering.

Artificial glaciers are best evaluated as a community water-security and climate-adaptation measure rather than as a glaciological intervention. Treating a village-scale adaptation technique as a large-scale glaciological intervention risks overstating its potential and obscuring the local need it addresses. The growing literature on the vulnerability of mountain water towers (Immerzeel et al., 2020) highlights the importance of that need, independent of any geoengineering framing.

Ice Sheet Stabilization via Seabed Curtains

Seabed curtains (also described as underwater barriers, ocean curtains, or flexible berms) are proposed structures anchored to the seafloor to block or redirect warm ocean water from reaching the grounding lines of marine-terminating glaciers. The concept has been proposed for both Antarctica and Greenland (Wolovick & Moore, 2018; Moore et al., 2018; Hunt & Byers, 2019). In Antarctica, the target is (modified) Circumpolar Deep Water (CDW), which is the dominant driver of submarine melt for many West Antarctic outlet glaciers, particularly in the Amundsen Sea sector (Jenkins et al., 2010; Keefer et al., 2023). In Greenland, the equivalent threat is warm Atlantic Water intruding into glacial fjords (Hopwood et al., 2025). If warm water could be blocked from reaching glacier fronts, basal melt rates may decrease, which may, in turn, slow grounding line retreat.

The concept has been proposed in several forms: a rigid seabed berm of fill material, or flexible buoyant curtain panels anchored to the seafloor and tensioned upward by their own buoyancy or rising fluid. Keefer et al. (2023) provide the most detailed engineering feasibility assessment to date, and Wolovick et al. (2023) evaluate potential curtain routes across the Amundsen Sea embayment using new multibeam bathymetry and a simple cost-benefit model. Hopwood et al. (2025) assess ecological and biogeochemical consequences in Greenland fjords. The principle of underwater curtains has been demonstrated at the scale of hydroelectric reservoirs by the deployment of temperature-control curtains (Keefer et al., 2023).

Outcome Reliability

Score: Uncertain **Confidence:** High

The outcome of seabed curtain deployment on ice shelf melt and grounding line stability is scientifically unresolved. While CDW intrusion is the dominant driver of basal melt for Amundsen Sea outlet glaciers, the effect of that melt is cumulative in time and evolves as the shape of the ice shelf does. It is currently unclear whether simply halting the flow of CDW into an affected shelf cavity is sufficient to stop grounding line retreat that has already commenced (e.g. van den Akker et al 2025, Zhao et al 2025), with the answer likely dependent on how much retreat has already occurred, the current state of the ice shelf, and the geometry of the glacier basin. Even for specific glaciers such as those in the Amundsen Sea, different models may predict divergent outcomes (Wolovick and Moore 2018, Alevropoulos-Borrill et al 2024, Bett et al 2024, van den Akker et al 2025). Localized blocking of currents through seabed curtains may also have unintended consequences by redirecting warm-water flow to other glacier basins and increasing mass loss there (Gürses et al. 2019).

Technological Readiness Level

1221 **Score:** Low **Confidence:** High

1222 TRL 1-3. Preliminary engineering designs exist (Keefer et al., 2023). The principle of
1223 underwater flexible barriers has been demonstrated at scale in freshwater hydroelectric
1224 reservoirs, providing proof-of-concept for the basic approach. Keefer et al. (2023)
1225 outline curtain panel components — buoyancy elements, tensile members, structural
1226 lattice, and low-permeability fabric — and assess four foundation configurations for
1227 different seabed conditions. They estimate that commercial fiberglass epoxy pipe can
1228 support curtains up to ~300 m height without additional reinforcement. However, no
1229 prototype has been built or tested in a marine polar environment. Plans announced in
1230 2024 by researchers at the University of Lapland and the University of Cambridge for
1231 small-scale model tests in a river, and possibly a prototype in a Norwegian fjord, were
1232 described as first steps toward physical testing (McKie, 2024). Key engineering
1233 unknowns include: materials withstanding saltwater corrosion and sustained
1234 oceanographic loading over a 25-year design life; anchoring systems on Antarctic
1235 seabed sediments; installation methods in ice-infested, remote, deep-water
1236 environments under short polar working seasons; and the fluid-structural dynamics of
1237 curtains under realistic oscillating loads (Keefer et al., 2023) as well as efficacy under
1238 field conditions involving tidal currents, surface wind forcing, and iceberg collisions.

1239 **Scalability**

1240 **Score:** Medium **Confidence:** Medium

1241 The modular panel design is physically scalable along a curtain route, and Wolovick et
1242 al. (2023) identify multiple viable routes in Pine Island Bay with varying cost-benefit
1243 profiles. The concept could in principle be extended to Greenland fjords as a lower-
1244 complexity stepping stone to Antarctic deployment (Keefer et al., 2023). However, scale-
1245 up efficiency in the Amundsen Sea is constrained by severe logistical bottlenecks: each
1246 additional curtain section requires icebreaker transits of over 2,500 km from Punta
1247 Arenas (the nearest major port), towing large structures across the Southern Ocean and
1248 through sea ice (Keefer et al., 2023; Siegert et al., 2025). Working seasons are short —
1249 probably less than 3 months per year — and frequently interrupted by sea ice and
1250 icebergs: 56% of research cruises to the region in the past several decades
1251 experienced at least partial disruption, and 22% could not reach their study regions at
1252 all (Siegert et al., 2023). Furthermore, multiple structures protecting several outlet
1253 glaciers simultaneously may be required, including at other vulnerable and even more
1254 remote margins such as the Cook Ice Shelf and the Mertz and Ninnis glaciers (Siegert
1255 et al., 2025), multiplying costs and environmental impact. **Scalability** is physically
1256 plausible but logistically constrained.

1257 **Timeliness for Near-Future Effects**

1258 **Score:** Low **Confidence:** High

1259 No meaningful deployment is likely to occur within 20 years. The research-to-
1260 deployment pathway requires: fundamental oceanographic and glaciological site
1261 characterization; fluid-structural engineering design and tank testing; prototype trials in
1262 temperate then sub-polar waters; Comprehensive Environmental Evaluation under the
1263 Madrid Protocol; political negotiation among all 29 Antarctic Treaty Consultative Parties;
1264 financing at tens-of-billions-of-dollars scale; and Antarctic construction logistics from
1265 scratch (Keefer et al., 2023; Siegert et al., 2025; Corbett & Parson, 2022). Keefer et al.
1266 (2023) state that any engineering solution would require at least a full decade of study
1267 before implementation, and estimate a further decade of construction.

1268 Even if a curtain were completed within 20 years, the glaciological response would likely
1269 be slow. Ice-sheet modeling of the Amundsen Sea Embayment suggests that reducing
1270 sub-shelf melt causes ice discharge to decline promptly, but grounding-line re-advance
1271 and stabilization unfold over one to two centuries, and reduced melt alone does not
1272 offset ice already lost (Alevropoulos-Borrill et al., 2024). Keefer et al. (2023) likewise
1273 frame the potential benefit as stabilizing Pine Island and Thwaites glaciers "over the
1274 next few centuries."

1275 Ice flow modeling of Sermeq Kujalleq, Greenland, found that 50 - 100 m barriers at the
1276 fjord sill made a negligible difference to projected terminus retreat through 2100 under
1277 both moderate and high emission scenarios, because the glacier is undergoing
1278 sustained retreat on a retrograde bed (Zhao et al., 2025).

1279 **Potential to Make a Difference in the Arctic**

1280 **Score:** Low **Confidence:** Medium

1281 Seabed curtains have been explicitly proposed for Greenland as well as Antarctica
1282 (Moore et al., 2018; Hunt & Byers, 2019). In Greenland, artificial barriers in glacial fjords
1283 could, in principle, prevent warm Atlantic Water from reaching marine-terminating
1284 glaciers, and fjord geometry makes this logistically less challenging than the open
1285 continental shelf setting of the Amundsen Sea (Siegert et al., 2025). Hopwood et al.
1286 (2025) provide the most detailed assessment of a Greenland application but primarily
1287 highlight the ecological and biogeochemical risks, while Zhao et al. (2025) argue that a
1288 curtain-type barrier may simply be ineffective at halting the retreat of at least one major
1289 Greenlandic outlet glacier that has already lost its floating tongue. A further key
1290 limitation is that the Greenland Ice Sheet is highly susceptible to atmosphere-driven
1291 surface melting, which seabed curtains cannot address — blocking submarine melt at
1292 glacier fronts would leave the growing surface-melt contribution entirely unaffected. The
1293 score reflects this critical limitation and the significant ecological concerns raised by
1294 Hopwood et al. (2025). Hunt & Byers (2019) proposed submerged barriers or rock-fill

dams at ten major Greenland outlet glaciers where the barrier depth would be less than 500 m, estimating that they could prevent up to 5.3 m of sea-level rise at a cost of about US \$0.275 billion per year. However, their benefit estimates relied on simple geometric assumptions (a uniform 150 km width and 1000 m thickness of affected ice) rather than ice flow or ocean modeling, and subsequent modeling of one of their proposed sites, Sermeq Kujalleq, found that a barrier would have a negligible effect on retreat (Zhao et al., 2025). The score reflects these limitations and the significant ecological concerns raised by Hopwood et al. (2025).

Potential to Make a Global Difference

Score: Uncertain **Confidence:** Low

The potential stakes are large, since ocean melting in the Amundsen Sea sector may already have destabilized ice equivalent to a metre or more of global sea level (Keefer et al., 2023). However, major science questions still need to be resolved, and it is unclear whether seabed curtains would significantly affect glacier discharge or stability. The score reflects this uncertainty, exacerbated by the inability to address atmosphere-driven melt in Greenland and the near-impossibility of deploying at meaningful scale quickly.

Cost to Benefit Comparison

Score: Uncertain **Confidence:** High

Keefer et al. (2023) estimate an 80 km curtain in the Amundsen Sea at \$40-80 billion capital over a decade plus \$1-2 billion/year maintenance — roughly \$5-10 per person per year for the ~200 million people projected to relocate due to coastal flooding. Keefer et al. (2023) compare this with projected sea dike capital investment of about \$40 billion/year for 1 m of sea-level rise, citing Brown et al. (2021), while acknowledging that curtain designs are too undeveloped for total costs to be estimated with great **Confidence**. However, Siegert et al. (2025) consider the Keefer cost estimate a likely significant underestimate: the Thames Barrier (500 m long, built in <10 m water adjacent to a major logistics hub) cost the equivalent of \$6.2 billion/km at 2024 prices, compared to Keefer's estimate of \$1 billion/km for an 80 km structure in 600 m water 2,500 km from the nearest port. The Three Gorges Dam cost approximately 25 times more per kilometer than the Amundsen Sea curtain estimate, and each new ice-strengthened vessel capable of the installation work would cost on the order of \$500 million (Siegert et al., 2025). The benefit side is also uncertain: Outcome Reliability is undetermined, and the timescale for any glaciological response extends well beyond current planning horizons.

Likelihood of Environmental Risks

1331 **Score:** High Risk **Confidence:** Medium

1332 Seabed curtain deployment poses significant near-term environmental risks. Key
1333 concerns include:

1334 Benthic ecosystem disruption: installation would disturb fragile deep-water seabed
1335 communities, including unique invertebrate assemblages adapted to cold, stable
1336 conditions (Gutt et al., 2021).

1337 Nutrient flux disruption: Hopwood et al. (2025) show, using fjord circulation modeling,
1338 that artificially shoaling the Ilulissat Icefjord sill from about 250 m to 100 m could halve
1339 seasonal nitrate fluxes from the fjord mouth with cascading consequences for marine
1340 productivity. Inner-fjord nutrient reservoirs may become progressively depleted over
1341 multiple seasons in ways that a single-season trial cannot detect. In Antarctica, curtains
1342 could similarly reduce the supply of iron from ice shelf cavities to the iron-limited
1343 Southern Ocean, with potential effects on productivity and the ocean carbon sink
1344 (Gürses et al., 2019; Hopwood et al., 2025; Siegert et al., 2025).

1345 Ocean circulation redistribution: as Gürses et al. (2019) show, blocking warm water at
1346 one point may redirect it to neighboring ice shelves or glacier fronts, potentially
1347 intensifying melt elsewhere and accelerating regional ice loss. Hunt & Byers (2019)
1348 identify the same risk in Greenland: reducing melt at glaciers with barriers could
1349 potentially warm the surrounding waters, increasing melt at glaciers without them, and
1350 would alter the temperature, salinity, and sea ice formation in the upper Arctic Ocean.

1351 Fisheries and migration disruption: Hopwood et al. (2025) flag that physical barriers in
1352 Greenland fjords could obstruct migration of Greenland halibut — local fishers report
1353 that the largest and most reproductively valuable individuals in Ilulissat Icefjord migrate
1354 out to spawn in January–February — with consequences for regional fish stocks and
1355 the fishers who depend on them.

1356 Installation noise and sediment release: pile driving and anchoring could generate
1357 intense underwater noise and sediment plumes. In shallow water, bubble curtains and
1358 silt curtains can mitigate these impacts, but the effectiveness of such measures is only
1359 partly established. Noise mitigation during German offshore wind farm construction
1360 reduced, but did not eliminate, disturbance of harbor porpoises (Brandt et al., 2018),
1361 and has not been demonstrated at the depths, currents, and ice conditions of polar
1362 continental shelves or fjords.

1363 Non-native species introduction: installation using structures towed from temperate
1364 ports may introduce non-native organisms to Antarctic or Arctic waters, with unknown
1365 ecological consequences.

1366 Material degradation and pollution: curtain panels designed for a 25-year life in
1367 sustained oscillating oceanographic loads could degrade and become marine debris
1368 (Siegert et al., 2025).

1369 **Effects on Indigenous/Local Communities**

1370 **Score:** Negative **Confidence:** High

1371 The Amundsen Sea is remote with no permanent human habitation or indigenous
1372 presence directly on site, so direct community impacts in Antarctica are limited to
1373 indirect effects via fisheries and oceanographic changes to CCAMLR-managed species.
1374 A deployment in Greenland would be substantially different: any fjord-based intervention
1375 would take place in or adjacent to waters used by Greenlandic communities for
1376 subsistence and commercial fishing. Hopwood et al. (2025) specifically flag that a
1377 barrier at the mouth of Ilulissat Icefjord could reduce the nutrient supply that sustains
1378 one of Greenland's largest inshore fisheries in Disko Bay and obstruct halibut migration,
1379 and conclude that the socio-economic consequences for local stakeholders would likely
1380 be negative whether or not the intervention reduced ice melt. Siegert et al. (2025)
1381 further note that Greenlandic communities would bear these local risks while gaining
1382 little direct benefit, because ice-sheet mass loss lowers relative sea level around
1383 Greenland.

1384 **Ease of Reversibility**

1385 **Score:** Low **Confidence:** Medium

1386 Curtain panels are designed to be detachable from foundations for repair, replacement,
1387 or removal (Keefer et al., 2023; Wolovick et al., 2023), which is a meaningful advantage
1388 over rigid sills. Hunt & Byers (2019) draw the same distinction for Greenland: modular
1389 barriers could be removed at relatively low cost but would last only 20–30 years,
1390 whereas rock-fill dams would be effectively permanent, with removal requiring an effort
1391 comparable to construction. However, foundations are intended to be effectively
1392 permanent once installed, with a 100-year design life (Keefer et al., 2023), and full
1393 reversal of ecological and oceanographic changes post-removal is uncertain. Changes
1394 to disturbed seabed communities and reorganized fjord circulation patterns could persist
1395 well beyond physical removal of the structures.

1396 **Likelihood of Termination Shock**

1397 **Score:** Some risk **Confidence:** Low

1398 Physical seabed structures do not produce the rapid atmospheric rebound associated
1399 with stratospheric aerosol injection termination shock. If a curtain were removed or
1400 failed, CDW would regain access to the sub-shelf cavity and ocean-driven melting
1401 would resume, with the glaciological response unfolding over years to decades rather

than as the abrupt atmospheric warming associated with SAI termination. However, Siebert et al. (2025) note that structural failure from iceberg collisions, strong currents, or foundation instability could compromise the entire intervention, and Keefer et al. (2023) acknowledge that the approach entails a maintenance commitment of hundreds of years. No studies have yet modeled the sudden removal of a seafloor barrier after a lengthy period of operation.

Suitability within Current Legal/Governance Structures

Score: Not possible **Confidence:** High

Antarctic governance presents serious obstacles. Any seabed construction in the Amundsen Sea would require a Comprehensive Environmental Evaluation at the highest level of scrutiny under Article 8 of the Madrid Protocol to the Antarctic Treaty, as it would have far more than a 'minor or transitory' impact (Siebert et al., 2025). The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) would also have concerns regarding marine ecosystem consequences. Obtaining international consensus to intervene in Antarctic processes at this scale has never been attempted before, and Flamm & Shibata (2025) point to significant potential for 'international discord' over authority, sovereignty, and security. Corbett & Parson (2022) argue that early-stage research could proceed under the existing system and that the governance challenges are ultimately surmountable, but conclude that the Madrid Protocol would very likely prohibit construction of ice-sheet stabilization interventions without amendment. In 2025, the Antarctic Treaty Consultative Meeting endorsed a precautionary approach towards all geoengineering activities in the Antarctic, following advice from its Committee for Environmental Protection that geoengineering methods should not be conducted there at this point because of their unknown environmental consequences (Siebert et al., 2025). Keefer et al. (2023) acknowledge the governance challenge extends 'far beyond the 29 consultative parties.'

In Greenland, governance rests with national jurisdiction (the Kingdom of Denmark, including Greenland) rather than an international treaty system (Siebert et al., 2025), and the most frequently discussed site, Ilulissat Icefjord, is a UNESCO World Heritage Site, which Hopwood et al. (2025) note makes it an unlikely location for any environmental intervention. For Greenland and other Inuit homelands, any large-scale intervention would require the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and set out as a minimum standard of engagement in the Inuit Circumpolar Council's Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC has no formal position on geoengineering, but considers it to fall under its commitment to Inuit self-determination, with the FPIC obligation extending to researchers as well as to deployment (Crump, 2025).

1440 **Amount of Attention within Academic/Media/Industry**

1441 **Score:** Medium

Confidence: High

1442 Seabed curtains have attracted meaningful and growing academic attention. Key peer-
1443 reviewed papers include Wolovick & Moore (2018), Keefer et al. (2023), Wolovick et al.
1444 (2023), Hopwood et al. (2025), Hunt & Byers (2019), and Siegert et al. (2025). The
1445 concept was identified as a priority research topic at the 2023 Chicago Glacial Climate
1446 Intervention workshop (MacAyeal et al., 2024). Corbett & Parson (2022) provide a
1447 dedicated legal analysis. Wang et al. (2025) review the concept within a comprehensive
1448 glacial geoengineering assessment. However, beyond the conceptual engineering
1449 assessment of Keefer et al. (2023), no peer-reviewed studies of materials testing, tank
1450 tests, or prototype trials have been published; small-scale physical tests were
1451 announced in 2024 by researchers at the University of Lapland and the University of
1452 Cambridge (McKie, 2024). Public media coverage is occasional and largely linked to
1453 broader Antarctic geoengineering stories. Public media coverage has grown since 2024,
1454 including news features in Nature (You, 2024) and Science (Richter, 2024) and
1455 international press coverage of planned field tests (McKie, 2024). Commercial interest is
1456 limited, although philanthropic funders have supported research workshops on the
1457 concept (MacAyeal et al., 2024). The medium rating reflects genuine scientific
1458 engagement at the conceptual level, without the depth of technical or institutional
1459 development needed for serious implementation consideration.

1460 **Overall Assessment**

1461 Seabed curtains represent one of the most physically direct concepts for addressing the
1462 dominant mechanism of West Antarctic Ice Sheet mass loss. The engineering concept,
1463 as developed by Keefer et al. (2023) and Wolovick et al. (2023), is more detailed than
1464 most glacial intervention proposals. The current scientific and engineering state of
1465 knowledge, however, is insufficient to determine whether this would translate into
1466 effective glacier stabilization. Several lines of evidence raise serious concerns.

1467 The ability to stop or reverse grounding line retreat in the Amundsen Sea by blocking
1468 ingress of mCDW remains in question, with divergent modeling results having emerged
1469 recently that largely suggest such an intervention may not suffice (Alevropoulos-Borrill
1470 et al., 2024; Bett et al., 2024; van den Akker et al., 2025). At a more detailed level, the
1471 work in Gürses et al (2019) suggests the Amundsen Sea oceanographic system may
1472 route warm water around any single barrier to other embayments, requiring a three-
1473 dimensional understanding of ocean circulation and the vulnerability of adjacent glacier
1474 catchments to the one being protected by a barrier.

1475 The ecological risks identified by Hopwood et al. (2025) and Siegert et al. (2025) are
1476 only partly quantified, although Hopwood et al. (2025) conclude that there is already

sufficient evidence that a barrier at Ilulissat Icefjord would have negative regional consequences for marine productivity. Nutrient flux disruption, migration barriers, non-native species introduction, and marine debris are all plausible consequences whose severity cannot currently be assessed.

The engineering challenges of constructing and maintaining structures at 500-1,000 m depth, at scales of tens to hundreds of kilometers, in one of the world's most remote and hostile marine environments are extreme. Cost estimates from Keefer et al. (2023) are likely significant underestimates given comparable real-world engineering benchmarks.

Key near-term research needs identified in the literature include improving understanding of CDW pathways in the Amundsen Sea; developing coupled ice-ocean models capable of resolving sub-shelf circulation at the resolution needed to assess curtain effects; conducting engineering feasibility assessments including fluid-structure dynamic simulations and tank tests; and pursuing ecological monitoring in analogous fjord environments. An orderly progression from temperate-water pilots to Greenland fjords before Antarctic deployment is recommended by Keefer et al. (2023) and Wolovick et al. (2023), but it is worth reiterating the ecological and economic risks (Hopwood et al., 2025) of doing so in Greenland (where glacial run-off, ocean primary productivity, fisheries and human populations are closely intertwined).

Ice Sheet Stabilization via Ice Shelf Buttressing

Ice shelf buttressing interventions aim to increase the resistive force that floating ice shelves exert against inland ice flow. Since nearly all large ice shelves are in Antarctica (Greenland retains only a few floating ice tongues, mainly in the north), this intervention focuses on the Antarctic Ice Sheet, particularly West Antarctica. The primary sub-approach is to construct artificial pinning points — submerged structures (e.g., interlocking arrays of reinforced concrete caissons anchored to the seabed by drilled piles) on which the ice shelf would ground, adding resistance to flow (Wolovick & Moore, 2018; Lockley et al., 2020). Wolovick & Moore (2018) modeled artificial pinning points up to 300 m high; Siegert et al. (2025) report that this idea has since been discarded by its proponents in favor of seabed curtains (see Assessment 6).

Artificially enhancing ice shelf resistance could slow grounding line retreat driven by Marine Ice Sheet Instability (MISI) and reduce contributions to sea level rise from outlet glaciers such as Thwaites and Pine Island (Moore et al., 2018; Wolovick & Moore, 2018). However, the fundamental science underpinning this intervention remains contested, engineering implementation faces severe practical obstacles, and additional environmental and governance barriers make deployment in the foreseeable future extremely unlikely.

Outcome Reliability

Score: Uncertain

Confidence: High

"Buttressing" refers to the reduction in stress at the grounding line caused by the presence of an ice shelf subject to drag either from its sides or from ice rises and ice rumples caused by bedrock highs that contact the ice shelf in the interior of an embayment. The proposed interventions, to the extent that they have been fully articulated, would harness this effect in order to halt grounding line retreat in vulnerable embayments. The ability of ice shelves to stabilize a grounding line in an otherwise unfavorable position on a reverse slope hinges on the shelf being confined in a sufficiently narrow embayment (e.g. Goldberg et al., 2009; Schoof et al, 2017), and on the length of the ice shelf not being limited by ocean-driven basal melting (Haseloff & Sergienko, 2018). It is possible in idealized simulations to cause grounding line advance through introducing a bedrock high in the middle of an ice shelf that is otherwise too wide (Goldberg et al., 2009, section 5.3), but these simulations have so far omitted processes such as fracturing and basal melting. Under certain circumstances, pinning points can lead to stresses that cause fractures and contribute to ice shelf instability: the recent fragmentation of the Thwaites Eastern Ice Shelf has been attributed to backstress from its pinning point acting on progressively weakening ice (Benn et al., 2022). Analysis of natural pinning points on the Ross Ice Shelf also indicates that their mechanical effect depends less on their size than on the properties of the seafloor

materials (Still et al., 2019). Recent modeling studies also highlight strong spatial variability in the buttressing effect ([Fürst et al., 2015](#); [Sergienko et al., 2024](#)), making the effect of pinning point placement uncertain in practice.

The ice shelves of the Amundsen Sea glaciers (Thwaites, Pine Island) are heavily fractured, and thinning as a result of rapid sub-shelf melting (e.g. Pritchard et al., 2012; Paolo et al., 2015; Benn et al., 2022). Lockley et al. (2020) therefore propose building artificial pinning points in open water beyond the present ice front. These would become useful only after the ice shelf had first been made to advance by other means, such as blocking warm water from reaching it (Lockley et al., 2020). The same rapid basal melting is a problem for the modeling evidence, because idealized simulations that show pinning points stabilizing a grounding line generally leave basal melting out. Wolovick & Moore (2018) did include basal melting in their simulations, and found that success was sensitive to when and where the artificial pinning points were placed.

Technological Readiness Level

Score: Low **Confidence:** High

No peer-reviewed prototype or field demonstration exists. Conceptual designs include reinforced-concrete caissons, thermosyphon arrays, and tensile reinforcements ([Lockley et al., 2020](#)), but none has been tested. Construction beneath ice shelves in remote, sea ice-dominated environments — at depths of hundreds of meters, resisting crushing ice loads and saltwater corrosion over decades — far exceeds demonstrated capabilities. [Wang et al., 2025](#) and [MacAyeal et al., 2024](#) confirm the knowledge base needed to design a credible intervention is still being assembled. A fundamental feasibility limitation is that structures would have to be built either beneath a floating ice shelf (for example using submersibles) or in open water to be overridden by an advancing shelf; removing ice to gain access would itself risk destabilizing the shelf (Lockley et al., 2020).

Scalability

Score: Low **Confidence:** High

Buttressing is inherently localized and spatially sensitive. Artificial pinning points must be sited with extraordinary precision relative to ice stream geometry and grounding line position ([Fürst et al., 2015](#)), and the spatial variability of effective buttressing ([Sergienko et al., 2025](#)) means there is no simple formula for determining how many structures are needed. Thwaites Glacier spans ~120 km at the grounding line; meaningful stabilization would require numerous structures across a hostile, poorly accessible seabed ([Siegert et al., 2025](#)), with each additional structure multiplying cost, logistical complexity, and governance burden.

1571 **Timeliness for Near-Future Effects**

1572 **Score:** Low **Confidence:** High

1573 No meaningful deployment could be in place within 20 years. Required steps —
1574 glaciological and oceanographic research, engineering design and prototyping,
1575 Comprehensive Environmental Evaluations under the Madrid Protocol, governance
1576 negotiations, financing at hundreds of billions of dollars, and Antarctic construction —
1577 each take years to decades ([Siegert et al., 2025](#)). The 2025 ATCM endorsement of a
1578 precautionary approach towards geoengineering in the Antarctic adds a further
1579 governance hurdle (Siegert et al., 2025). [MacAyeal et al., 2024](#), who advocate for
1580 research on glacial interventions, propose a research agenda for the next decade rather
1581 than deployment.

1582 **Potential to Make a Difference in the Arctic**

1583 **Score:** Low **Confidence:** High

1584 Ice shelf buttressing is specific to Antarctic outlet glaciers. Greenland's outlet glaciers
1585 generally lack the extensive floating ice shelves that characterize Antarctic outlets;
1586 where they terminate in fjords, buttressing is provided mainly by the fjord walls rather
1587 than by pinning points beneath floating ice ([Lockley et al., 2020](#)). The main exceptions
1588 are the few remaining floating ice tongues in north Greenland (e.g., Petermann, Ryder,
1589 79°N Glacier), which are themselves thinning and disintegrating under ocean warming
1590 (Millan et al., 2023). This intervention offers no discernible benefit to Arctic or northern
1591 regional ecosystems or communities.

1592 **Potential to Make a Global Difference**

1593 **Score:** Low **Confidence:** High

1594 A technically successful intervention could in principle reduce WAIS contributions to sea
1595 level rise over centuries — with enormous consequences for hundreds of millions of
1596 coastal inhabitants ([Brown et al., 2021](#); Depsky et al., 2023). However, this is heavily
1597 qualified by the very low assessed probability of technical success, long timescales
1598 before any measurable effect, and the risk that construction or structural failure could
1599 weaken rather than strengthen the ice shelf (Benn et al., 2022; [Lockley et al., 2020](#)).

1600 **Cost to Benefit Comparison**

1601 **Score:** Prohibitive **Confidence:** High

1602 No reliable cost estimates exist, but all analyses suggest costs in the hundreds of
1603 billions of dollars or more, with deeply uncertain and potentially zero benefit. [Siegert et](#)
1604 [al., 2025](#) estimate that polar geoengineering would require hundreds of billions of
1605 dollars in initial costs, plus decades of maintenance. Corbett & Parson (2022), drawing

on Wolovick & Moore (2018), note that pinning points would require volumes of material comparable to the artificial islands built in Dubai and Hong Kong, in a far more remote and hostile setting. The risk of structural failure is substantial, given the failure modes identified by [Lockley et al., 2020](#) (tearing from moorings, bending/shear failure, saltwater corrosion, freeze-thaw fracture, crushing), including tearing from moorings, snapping under bending and shear loads, abrasion, saltwater corrosion of reinforcement, freeze-thaw fracture of concrete, and crushing. Compared to direct coastal adaptation ([Brown et al., 2021](#)) or emissions mitigation, the cost-benefit ratio is highly unfavorable.

Likelihood of Environmental Risks

Score: High risk **Confidence:** Medium

Significant and largely unquantified environmental risks accompany large-scale Antarctic seabed construction. Key risks include:

Benthic ecosystem disruption: seabed structures would physically disturb fragile Antarctic benthic communities adapted to cold, stable conditions ([Gutt et al., 2021](#)). Construction would also introduce underwater noise and vessel traffic affecting marine mammals (Erbe et al., 2019), and floated-in structures could introduce non-native species (Siegert et al., 2025).

Nonlinear system responses: [Lockley et al. \(2020\)](#) caution that, because the ice-ocean system contains uncertain nonlinear feedbacks, any intervention that disturbs a stabilizing element (for example, removing part of an ice shelf to build a pinning point) could trigger runaway ice loss, such as marine ice-cliff failure.

Counterproductive fracturing: Benn et al. (2022) show that backstress from a pinning point can fracture and fragment a weakening ice shelf, the opposite of the intended effect.

Effects on Indigenous/Local Communities

Score: Neutral **Confidence:** Low

Antarctica has no indigenous population. If effective, a global reduction in sea level would benefit low-lying coastal and island communities worldwide. Conversely, construction activities and vessel traffic in the Southern Ocean could disturb marine mammals ([Erbe et al., 2019](#)) and CCAMLR-managed fisheries. On balance, effects are assessed as neutral, with the caveat that communities most vulnerable to sea level rise have had little voice in discussions of this intervention, although the authors of a recent research white paper call for stakeholders in the Global South and the Arctic to be included in any research ([MacAyeal et al., 2024](#)).

1641 **Ease of Reversibility**

1642 **Score:** Low **Confidence:** Medium

1643 Caissons anchored by drilled piles on the Antarctic seabed could not be readily
1644 removed, and the Madrid Protocol requires abandoned work sites to be cleaned up
1645 (Corbett & Parson, 2022). Removal operations in polar waters would be technically
1646 demanding and expensive, and researchers have advised caution about installing
1647 equipment that would later need to be removed ([Lockley et al., 2020](#)). If the intervention
1648 worked, ice would ground on these structures, making removal essentially impossible.
1649 Overall reversibility is poor.

1650 **Likelihood of Termination Shock**

1651 **Score:** Some risk **Confidence:** Medium

1652 Abandonment of physical buttressing structures would not cause an abrupt termination
1653 shock. However, an intervention could succeed for a time and then fail, bringing
1654 renewed ice loss and more rapid sea-level rise (Corbett & Parson, 2022), and structural
1655 failure (as opposed to planned termination) could cause localized abrupt events such as
1656 ice shelf fragmentation (Benn et al., 2022). The 'some risk' score reflects these
1657 possibilities.

1658 **Suitability in Current Legal Structures**

1659 **Score:** Not possible **Confidence:** High

1660 All proposed buttressing interventions would trigger Comprehensive Environmental
1661 Evaluations under Article 8 of the Madrid Protocol (Siegert et al., 2025), and Corbett &
1662 Parson (2022) conclude that the Protocol would very likely prohibit construction of ice-
1663 sheet stabilization structures without amendment. At the most recent ATCM (Milan,
1664 June–July 2025), the Committee for Environmental Protection advised that
1665 geoengineering methods in the Antarctic should not be conducted at this point, and the
1666 ATCM endorsed a precautionary approach towards all geoengineering activities in the
1667 Antarctic, with most Consultative Parties concluding that none of the assessed options
1668 met essential criteria for being safe, responsible, or feasible ([Siegert et al., 2025](#)).

1669 This intervention is not being proposed for Greenland, but if it were, it would require the
1670 free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN Declaration
1671 on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and set out as a
1672 minimum standard of engagement in the Inuit Circumpolar Council's Circumpolar Inuit
1673 Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC has no formal
1674 position on geoengineering, but considers it to fall under its commitment to Inuit self-
1675 determination, with the FPIC obligation extending to researchers as well as to
1676 deployment (Crump, 2025).

1677 **Attention from Public**

1678 **Score:** Low **Confidence:** High

1679 The concept has attracted meaningful but not deep academic attention, primarily within
1680 specialized glaciology and geoengineering communities, with a limited public profile and
1681 essentially no commercial interest. Earlier concept papers ([Moore et al., 2018](#); [Wolovick
1682 & Moore, 2018](#)) generated discussion, and recent systematic reviews ([Wang et al.,
1683 2025](#); [Siegert et al., 2025](#)) reflect growing engagement with glacier geoengineering
1684 broadly. However, attention to buttressing specifically remains limited: Siegert et al.
1685 (2025) report that the artificial pinning point idea has been discarded by its proponents
1686 in favour of seabed curtains, and the 2023 Chicago and Stanford workshops focused on
1687 curtains and basal hydrology rather than pinning points (MacAyeal et al., 2024). The low
1688 rating reflects this.

1689 **Overall Assessment**

1690 Fundamental scientific questions — how much buttressing force is needed, where
1691 structures must be placed, how long they would function, and what the realistic
1692 probability of glaciological stabilization is — remain unanswered. Modeling tools and
1693 observational datasets needed to constrain these questions do not yet exist for the
1694 critical Amundsen Sea glaciers ([Sergienko et al., 2025](#); [Siegert et al., 2025](#)).
1695 Engineering challenges — constructing and maintaining structures at hundreds of
1696 meters depth in Antarctic conditions, across glaciers spanning tens to hundreds of
1697 kilometers — would require decades and currently unavailable resources. Structures
1698 would have to be built either beneath a floating ice shelf or in open water to be
1699 overridden by an advancing shelf, and removing ice to build them could itself destabilize
1700 the shelf (Lockley et al., 2020). The 2025 ATCM endorsement of a precautionary
1701 approach towards geoengineering, and the likely need to amend the Madrid Protocol
1702 (Corbett & Parson, 2022), represent concrete legal barriers.

1703 Key near-term research needs include: improving coupled ice-sheet/ocean models,
1704 characterizing buttressing and pinning point dynamics, and understanding how
1705 Amundsen Sea ice shelves respond to thermal and mechanical perturbations. This
1706 research informs sea level projections regardless of whether buttressing interventions
1707 are ever deployed.

1708

1709 Ice Sheet Stabilization by Basal Drying

1710 It has been proposed that ice sheets could be stabilized by reducing the lubricating
1711 effect of water at their base. Pressurized subglacial water, produced by geothermal
1712 heating, frictional heating, or surface meltwater draining to the bed, reduces friction at
1713 the interface between glacier ice and bedrock, allowing ice streams and outlet glaciers
1714 to flow more rapidly toward the ocean (Bennett, 2003). Reducing basal water through
1715 pumping water out of the glacier or ice sheet bed or freezing it in place could, in
1716 principle, slow ice stream velocity and reduce dynamic discharge to the grounding zone.

1717 Two main technological approaches are proposed: (1) pumping subglacial water out
1718 through boreholes drilled through the ice; and (2) cooling the subglacial interface
1719 through thermosyphon arrays or injection of coolants such as liquid CO₂. Hot water
1720 drilling has been demonstrated for scientific purposes — most extensively at the
1721 IceCube Neutrino Observatory, where 86 boreholes were drilled to depths of 2.5 km
1722 (Talalay, 2013; Corbett & Parson, 2022) — but conversion to an operational intervention
1723 platform with boreholes that remain open for an extended period of time represents a
1724 significant and uncharacterized engineering challenge.

1725 A critical and underappreciated risk is that intervention in the subglacial hydrological
1726 system could produce non-linear dynamic consequences, including the creation of an
1727 inefficient drainage system which could increase basal motion, ice build-up and surging,
1728 or paradoxical grounding zone retreat, all of which would have the opposite effect on
1729 sea level to that intended (Lockley et al., 2020). These risks are currently unquantified.

1730 **Outcome Reliability**

1731 **Score:** Uncertain **Confidence:** High

1732 The effect of basal water removal on ice sheet dynamics is scientifically plausible but
1733 deeply uncertain. In a sort of natural experiment, the Kamb Ice Stream in Antarctica
1734 stagnated, most likely due to a loss of water supply (Alley et al., 1994; Anandakrishnan
1735 & Alley, 1997). Subglacial water clearly plays an important role in determining basal
1736 friction and motion, but the effects can be non-intuitive. For example, in areas of
1737 seasonal surface melt, an initial addition of water leads to a well-documented spring
1738 speed-up. Continued input of water often helps create a more efficient drainage system
1739 following that initial speed-up, leading to a commonly observed reduction in ice flow
1740 throughout the melt season. This is well observed (e.g., Sundal et al., 2011) and is also
1741 evidenced in models (e.g., Werder et al., 2013).

1742 The relationship between water removal and long-term glacier dynamics is therefore
1743 non-linear and difficult to assess because it depends strongly on both the nature and
1744 current state of the system. Four critical risks exist: (1) removal of water could lead to a
1745 less efficient drainage system and higher rates of basal motion, (2) drainage

reorganization may deliver water more efficiently elsewhere, producing no net reduction in velocity; (3) reduced ice flow could cause ice to build up and eventually surge, rapidly delivering accumulated ice to the grounding zone once a surge commences (Kamb et al., 1985); and (4) reduced ice flux to the grounding zone could paradoxically trigger shrinkage of buttressing ice shelves and grounding zone retreat, as rates of frontal ablation can no longer be balanced by the reduced ice supply. This could trigger or exacerbate the Marine Ice Sheet Instability in regions of reverse bed slopes (e.g., Weertman, 1974). None of these potential responses has been modeled in sufficient depth to bound the probability of success versus failure.

Recently, Meyer et al. (2026) used an ice sheet model coupled to a subglacial drainage model to investigate the effect of pumping out water on ice motion. They applied the model to Helheim Glacier in Greenland and Thwaites Glacier in Antarctica; the latter of which is an often-cited target for an intervention. In their Thwaites experiment, Meyer et al. (2026) distributed 11 boreholes and pumped water from each at a rate of 1 m³/s (11 m³/s in total) for a year, which slowed the main trunk of the glacier by roughly 1%. Pumping at 11 sites on Helheim Glacier produced a comparable slowdown (Meyer et al., 2026). There are many uncertainties in such models due to the unknown nature of the glacier bed and the crude parameterizations necessary in a subglacial water flow model. However, it should be noted that the modeled pump rate is extremely high. For comparison, the biggest existing hot water drilling project, the IceCube Neutrino Observatory, pumped water at a rate of about 0.012 m³/s. Furthermore, it is a common experience in hot water drilling that boreholes do not connect to an active subglacial water system (Rada and Schoof, 2023) and would thus not be suitable for continuous removal of water. Finally, pumping lowers the water pressure around each borehole (Meyer et al., 2026), which would lower the water level in the borehole and increase the height through which water must be lifted, posing a significant challenge for pumping. Conventional hot water drilling relies on the fact that the water level in a borehole is typically either close to overburden or determined by the depth of firn, which limits the amount of necessary gravitational lift for recirculation.

Technological Readiness Level

Score: Low **Confidence:** High

Basal drying as a deliberate intervention has not been prototyped. The enabling technologies — deep ice drilling, subglacial water detection, pumping, and cooling — exist in various forms but have not been combined for this purpose. Scientific boreholes are drilled singly and are not typically used for long-term pumping or cooling. Thermosyphon technology is used in permafrost applications, on the scale of several meters (Wagner, 2004). It has been proposed for subglacial cooling (Lockley et al., 2020), but not tested or seriously explored in ice sheet conditions. Existing geothermal

thermosyphon systems and investigations (e.g., Chen et al., 2022) rely on a convecting “working fluid” that vaporizes at the bottom of the thermosyphon and involve significantly higher temperature gradients than those found in glacial systems. While suitable fluids exist (ammonia being a prominent example with a sufficiently low boiling point), the need to maintain a vapor-filled thermosyphon inside a ~1 km thick viscously creeping ice sheet points to significant design challenges and material costs, as a heavily armored borehole casing would no doubt be required; glacial boreholes that are required to remain open for extended periods of time, such as those used for ice coring, are typically filled with a neutrally buoyant fluid to prevent creep closure. No system integration has been designed or prototyped. The combined system remains at TRL 1–3.

Scalability

Score: Low **Confidence:** High

Scaling basal drying to meaningful ice sheet areas likely faces prohibitive logistical challenges. Accessing, monitoring, and modifying the subglacial water system with a significant impact on ice flow would likely require drilling through ice several kilometers thick at hundreds of separate sites on a continuously moving glacier, with each borehole needing maintenance against freezing and ice deformation for years or decades. Radar surveys can detect subglacial lakes but cannot map water routing at the precision needed to site boreholes effectively, and subglacial drainage is highly variable in space and time (Siegert et al., 2016). Ice motion of meters to kilometers per year means boreholes would progressively move away from their intended locations, requiring continuous new drilling. Lockley et al. (2020) note that water may not be extractable more than about 30 m from a borehole in a distributed drainage system, so slowing an ice stream would require dense fields of boreholes over a substantial area. Because ice motion steadily carries each borehole away from its target, these fields would have to be continually re-drilled.

If water can be successfully removed from the subglacial environment, it would have to be dealt with at the surface, presumably by turning it into snow, which would then have to be managed. The 1 m³/s extracted at each borehole in the Meyer et al. (2026) study would produce enough snow to cover a 1 km² area to a depth of 60 m in a year, or roughly 17 cm every day. For comparison, the South Pole station is dealing with significant drifting problems in an environment of about 20 cm of snow accumulation in a year (Zhai et al., 2023).

Extracting water at the rates used by Meyer et al. (2026), against a falling borehole water level, would require substantial continuous power at each borehole (Siegert et al., 2025), not including the energy needed to keep boreholes from freezing or any infrastructure that would need to be maintained. This would require an almost

1822 continuous supply of diesel fuel via ski-equipped aircraft or overland transport routes,
1823 which are extremely challenging to establish and maintain near fast-flowing ice, which
1824 would be the target.

1825 **Timeliness for Near-Future Effects**

1826 **Score:** Low **Confidence:** High

1827 Basal drying is unlikely to meaningfully contribute to sea level reduction within 20 years.
1828 The basic science of subglacial hydrology at relevant scales is insufficient to design an
1829 effective intervention. Even if subglacial water removal were demonstrated at a single
1830 glacier, the modeled effects are small (about a 1% slowdown; Meyer et al., 2026), and a
1831 measurable effect on sea level would require sustained operation at many sites for
1832 decades. The 20-year window is incommensurate with the research and physical
1833 response timescales involved.

1834 **Potential to Make a Difference in the Arctic**

1835 **Score:** Low **Confidence:** High

1836 Greenland outlet glaciers have active subglacial hydrological systems fed by surface
1837 meltwater drainage, fundamentally different from the basal melt systems of Antarctic ice
1838 streams (Das et al., 2008; Zwally et al., 2002). The Greenland subglacial water system
1839 responds dynamically to surface melt inputs on seasonal timescales; attempting to drain
1840 it faces the same challenges as the Antarctic application, plus the additional
1841 complication of continuous summer melt recharge effectively refilling any drained water,
1842 with refilling happening at rates significantly greater than those considered for pumping
1843 by Meyer et al. (2026). Siegert et al. (2025) further note that routing more meltwater to
1844 the bed in Greenland tends to create efficient, low-pressure channels that reduce
1845 annual ice velocities, and consider it highly unlikely that basal water extraction would be
1846 a feasible means of slowing Greenland's glaciers; it may even have the reverse effect.
1847 The technique offers little to Arctic mountain glaciers for similar reasons. Arctic and
1848 northern potential is low.

1849 **Potential to Make a Global Difference**

1850 **Score:** Low **Confidence:** Medium

1851 Apart from the idealized experiments of Meyer et al. (2026), the effect of an intervention
1852 on glacier dynamics has not been modeled, and no quantitative estimates exist for
1853 potential sea level reduction even under optimistic assumptions. Any intervention would
1854 affect a single outlet glacier or a small group. Multiple major outlet glaciers contribute to
1855 Antarctic and Greenland mass loss, each requiring independent studies. Global impact
1856 depends entirely on the unresolved question of whether the technique can be made to
1857 work at any single glacier (Moore et al., 2018; Siegert et al., 2025). Even if the results of

1858 Meyer et al. (2026) were to prove correct and the technology feasible, only about a 1%
1859 reduction of ice flux at a few target sites could be achieved, and an intervention at an
1860 even larger scale than that considered by these authors would be needed to make a
1861 meaningful contribution to reducing global sea level rise.

1862 **Cost to Benefit Comparison**

1863 **Score:** Prohibitive **Confidence:** Medium

1864 No published cost estimates exist. A minimum order-of-magnitude estimate can be
1865 derived from the IceCube Neutrino Observatory, which cost approximately USD \$280
1866 million for 86 boreholes, and from the Lake Ellsworth program, which spent about USD
1867 \$13 million in 2012 attempting a single 3 km borehole intended to remain open for 24
1868 hours (Siegert et al., 2025). Unlike the South Pole, none of the relevant proposed sites
1869 has existing infrastructure, and Siegert et al. (2025) suggest that a new coastal station
1870 would take decades to enact. Scaling to the hundreds of boreholes needed across an
1871 ice stream catchment — with pumping, cooling, and monitoring infrastructure, plus the
1872 ongoing maintenance burden of a continuously moving ice sheet — suggests costs in
1873 the tens to hundreds of billions of dollars. The benefit side is undefined because
1874 outcome reliability is uncertain and no credible sea level reduction estimate exists.

1875 **Likelihood of Environmental Risks**

1876 **Score:** Medium risk **Confidence:** Medium

1877 Basal drying poses significant and largely uncharacterized environmental risks:

1878 Subglacial microbial ecosystem disruption: subglacial environments harbor unique
1879 microbial communities of scientific value (Priscu et al., 2021). Drilling, pumping, and
1880 chemical cooling could disturb or destroy these communities at intervention sites, and
1881 Antarctic Treaty Parties have required proven sterilization of drilling water for subglacial
1882 access (Siegert et al., 2025). MacAyeal et al. (2024) argue that active ice-stream beds
1883 host little endemic biosphere, but subglacial microbiology is a young field.

1884 Fuel and chemical spills: drilling and maintaining hundreds of boreholes would require
1885 large quantities of fuel, drilling fluids, and coolants, with substantial spill risk in a pristine
1886 environment.

1887 Unintended dynamic consequences: basal water removal could trigger ice sheet
1888 surging, grounding zone retreat, or other non-linear responses that accelerate rather
1889 than reduce sea level rise. Lockley et al. (2020) warn explicitly that we should fear
1890 nonlinearities in the system, particularly apt for an intervention targeting the poorly
1891 understood subglacial hydrological system.

1892 **Effects on Indigenous Communities**

1893	Score: Negative	Confidence: Medium
1894	Antarctic interventions have no direct effects on indigenous communities. Greenland	
1895	interventions would require engagement with the Greenland Government and Inuit	
1896	communities under FPIC principles, and the massive logistical footprint would have	
1897	large impacts on local communities and infrastructure. Siegert et al. (2025) note that	
1898	Greenlandic communities would bear local risks with little direct benefit, because ice	
1899	loss lowers relative sea level around Greenland. The primary indirect benefit — reduced	
1900	sea level rise globally The primary indirect benefit — reduced sea level rise globally —	
1901	is contingent on outcome reliability that remains undetermined.	
1902	Ease of Reversibility	
1903	Score: Uncertain	Confidence: Medium
1904	Individual boreholes would freeze over and seal naturally if pumping ceased — a form	
1905	of automatic reversibility for the physical infrastructure. However, changes to subglacial	
1906	water routing and drainage pathways could persist longer, and the timescale of natural	
1907	recovery is unknown. If the intervention had produced changes to ice dynamics —	
1908	either the intended slowdown or unintended surging or grounding zone retreat — these	
1909	would persist on glacier-dynamic timescales of decades to centuries regardless of	
1910	borehole maintenance. Reversibility of the physical infrastructure is medium;	
1911	reversibility of glaciological consequences is unknown.	
1912	Likelihood of Termination Shock	
1913	Score: Some risk	Confidence: Low
1914	Abrupt cessation of basal water removal would allow subglacial water to reaccumulate,	
1915	potentially restoring lubrication more rapidly than it was removed. If the intervention had	
1916	successfully slowed ice flow, the return of basal water could trigger rapid return to pre-	
1917	intervention velocities or faster, delivering previously retained ice more rapidly to the	
1918	grounding zone. The surging instability scenario could have especially severe	
1919	termination effects if surge conditions had developed in response to the intervention.	
1920	Siegert et al. (2025) also note that even if drainage slowed one area, upstream	
1921	thickening would displace basal water into neighboring regions and could accelerate	
1922	flow elsewhere, the ‘water piracy’ mechanism linked to the shutdown of the Kamb Ice	
1923	Stream, which may reactivate this century. These risks are theoretical and unquantified,	
1924	but warrant a ‘some risk’ score.	
1925	Suitability in Current Legal Structures	
1926	Score: Not possible	Confidence: High

1927 Antarctic basal drying would be unlikely to gain approval under the current Antarctic
1928 Treaty System. Any borehole program at the required scale would trigger CEE-level
1929 review under the Madrid Protocol, and the 2025 ATCM precautionary moratorium
1930 recommendation against Antarctic geoengineering would further obstruct approval
1931 ([Siegert et al., 2025](#)).

1932 For Greenland and other Inuit homelands, any large-scale intervention would require
1933 the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN
1934 Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and
1935 set out as a minimum standard of engagement in the Inuit Circumpolar Council's
1936 Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC
1937 has no formal position on geoengineering, but considers it to fall under its commitment
1938 to Inuit self-determination, with the FPIC obligation extending to researchers as well as
1939 to deployment (Crump, 2025).

1940 **Attention from Public**

1941 **Score:** Medium **Confidence:** High

1942 Basal drying has received some academic attention primarily within broader
1943 geoengineering reviews (Moore et al., 2018; Lockley et al., 2020; Wang et al., 2025;
1944 Siegert et al., 2025) and occasional public media coverage, and basal hydrology
1945 interventions were one of two main foci of the 2023 Chicago and Stanford workshops
1946 (MacAyeal et al., 2024). The concept gained popular cultural traction from Kim Stanley
1947 Robinson's novel *The Ministry for the Future*. However, dedicated peer-reviewed
1948 research—including hydrological modeling, engineering design studies, or field
1949 experiments—has been almost entirely absent, except for recent work by Meyer et al.
1950 (2026). Academic engagement remains at the conceptual proposal level rather than
1951 technology development. The medium rating reflects broader-than-fringe awareness
1952 without substantive technical development.

1954 **Overall Assessment**

1955 Basal drying rests on a real physical observation — subglacial water lubricates ice flow
1956 — but the leap from observation to intervention is not coherent at the level of science
1957 currently available. Subglacial hydrology is one of the least understood components of
1958 the ice sheet system. Water beneath ice sheets does not behave as a simple reservoir
1959 that can be drained: it moves through a complex, spatially heterogeneous network of
1960 channels, cavities, and saturated sediments that responds non-linearly to perturbations,
1961 reorganizes dynamically, and varies substantially across different glacier types, bed
1962 geologies, and thermal regimes. The science does not yet exist to predict how this
1963 system would respond to deliberate interference at any scale.

1964 Engineering obstacles compound the scientific ones: drilling, monitoring, and pumping
1965 at hundreds of sites across moving, kilometer-thick ice would be required, and the 2025
1966 ATCM endorsement of a precautionary approach towards geoengineering adds a
1967 governance barrier. But these are secondary to the more fundamental problem: without
1968 a predictive understanding of subglacial water routing, it is not possible to design an
1969 intervention that reliably reduces ice velocity. The identified risks (drainage
1970 reorganization, surging instability, paradoxical grounding zone retreat) may simply be
1971 fatal rather than amenable to management. They reflect the state of scientific
1972 uncertainty about how the system works, and any one of them could produce outcomes
1973 worse than no intervention.

1974

Draft for Review

1975 **Pumping of Water onto Ice Sheets**

1976 This intervention proposes to increase ice sheet mass by pumping water, most likely
1977 desalinated seawater, onto the ice sheet surface, where it would freeze and increase
1978 surface mass balance with the goal of partially offsetting dynamic ice loss. The most
1979 commonly cited scenario involves deploying approximately 12,000 wind turbines to
1980 power pumps drawing seawater from the Southern Ocean, piping it to the ice sheet
1981 surface, and distributing it as snow over the Amundsen Sea sector of West Antarctica
1982 (Feldmann et al., 2019).

1983 Feldmann et al. (2019) modeled the mass addition required to stabilize the West
1984 Antarctic Ice Sheet and found that at least 7,400 Gt of ocean water would need to be
1985 deposited over 10 years, with lifting, desalination and heating requiring the electricity of
1986 about 12,000 high-end wind turbines. Frieler et al. (2016) estimate that pumping enough
1987 ocean water onto the Antarctic ice sheet to offset the currently observed rate of sea-
1988 level rise (about 3 mm per year) would require more than 7% of current global primary
1989 energy supply. Lockley et al. (2020) and Moore et al. (2018) discuss the concept in
1990 broader reviews of glacial geoengineering, noting the implausible resource
1991 requirements.

1992 **Outcome Reliability**

1993 **Score:** Low **Confidence:** Medium

1994 Outcome reliability is low. Even accepting that sufficient water could be pumped and
1995 frozen, a fundamental and unresolved problem is where the added water accumulates.
1996 Mass deposited near the coast, where it has the greatest effect on ice dynamics
1997 (Feldmann et al., 2019), is carried back to the ocean relatively quickly by ice flow,
1998 whereas storing at least 80% of the added ice for a millennium requires placing it at
1999 least 700 km from the coastline (Frieler et al., 2016). Water that does not freeze in place
2000 could pond, run off, or, where it reaches ice shelves or crevassed ice, promote
2001 hydrofracture (Lockley et al., 2020). Added mass in the wrong location relative to the ice
2002 dynamics could increase driving stress and outlet glacier flow rather than providing
2003 stabilizing buttressing (Lockley et al., 2020). The intervention therefore cannot reliably
2004 translate water deposition into the intended glaciological outcome.

2005 **Technological Readiness Level**

2006 **Score:** Low **Confidence:** High

2007 TRL 1. Pumps, desalination plants, and wind turbines exist individually, but their
2008 integration at the required scale in Antarctic conditions has no engineering basis.
2009 Antarctica's interior averages -57 degrees C with winds regularly exceeding 100 km/h;
2010 Siegert et al. (2025) note, in the context of powering subglacial drilling, that existing
2011 wind turbine structures on moving ice are several orders of magnitude smaller than

2012 would be necessary, and that operating year-round in extreme cold and wind is far
 2013 beyond current capabilities. Somewhat paradoxically, pumping water onto the ice sheet
 2014 would also have to include a mechanism for avoiding freezing, thus clogging the
 2015 pipeline. This would most likely have to be achieved via heating the seawater, further
 2016 adding to the energy cost (Feldmann et al., 2019).

2017 **Scalability**

2018 **Score:** Low **Confidence:** High

2019 The Feldmann et al. (2019) scenario requires about 740 Gt of water per year for a
 2020 decade, roughly a third of the total annual snowfall on the grounded Antarctic ice sheet,
 2021 concentrated over a single sector. The physical infrastructure required has no precedent
 2022 in human engineering history. Under continued warming, increasing melt rates would
 2023 demand ever-greater deposition volumes, and deposition would need to be sustained
 2024 after the initial decade (Siegert et al., 2025). **Scalability** is low.

2025 **Timeliness for Near-Future Effects**

2026 **Score:** Low **Confidence:** High

2027 No meaningful deployment could be completed within 20 years. Siegert et al. (2025)
 2028 note, for comparable large-scale polar engineering, that 'many of these challenges
 2029 require entirely new engineering approaches that would take many years, if not
 2030 decades, to develop, even with unlimited resources.' The 20-year window is entirely
 2031 incommensurate with the research and deployment timeline.

2032 **Potential to Make a Difference in the Arctic/Northern Regions**

2033 **Score:** Low **Confidence:** High

2034 Greenland presents additional fundamental problems: surface temperatures are
 2035 substantially warmer, and surface melt is already extensive across the ablation zone.
 2036 Pumped water would in many locations fail to freeze and instead add to runoff or drain
 2037 to the bed, worsening mass balance; surface melt already accounts for about half of
 2038 Greenland's mass loss and reaches the bed (Lockley et al., 2020). Frieler et al. (2016)
 2039 and Feldmann et al. (2019) consider only Antarctica, and no comparable proposal has
 2040 been made for Greenland. A related Arctic concept, pumping seawater onto sea ice to
 2041 thicken it (Desch et al., 2017), does not address ice sheet mass loss and faces similar
 2042 logistical limits (Siegert et al., 2025).

2043 **Potential to Make a Global Difference**

2044 **Score:** Low **Confidence:** High

2045 Feldmann et al. (2019) show that WAIS stabilization is theoretically achievable at
2046 sufficient scale, but that scale (7,400 Gt over 10 years, or roughly a third of Antarctica's
2047 total annual snowfall each year) exceeds all plausible infrastructure capacity. Continued
2048 atmospheric warming would require ever-increasing deposition rates. Global potential is
2049 low.

2050 **Cost to Benefit Comparison**

2051 **Score:** Prohibitive **Confidence:** High

2052 No reliable cost estimate exists. Frieler et al. (2016) do not estimate monetary costs, but
2053 their energy estimate (more than 7% of current global primary energy supply to offset
2054 the current rate of sea-level rise) implies very high costs, against uncertain and
2055 potentially negative benefits given the accumulation location problem. Brown et al.
2056 (2021) and Depsky et al. (2023) quantify global coastal adaptation costs and avoided
2057 damages, providing a benchmark against which the costs of this approach would need
2058 to be compared. Cost-benefit is prohibitive.

2059 **Likelihood of Environmental Risks**

2060 **Score:** High risk **Confidence:** Medium

2061 Feldmann et al. (2019) acknowledge that the required infrastructure could mean losing
2062 a unique natural reserve, with serious effects on sensitive marine and coastal
2063 ecosystems. Key risks:

2064 Ecosystems: Large-scale seawater intake and discharge of desalination brine affecting
2065 coastal marine ecosystems; Hopwood et al. (2025) show that glacier geoengineering
2066 more broadly can alter nutrient supply and productivity in ecosystems that support
2067 fisheries.

2068 Pollution: Construction pollution, fuel contamination, and persistent debris in one of the
2069 world's most pristine environments, with no capacity for remediation.

2070 Albedo reduction: melt could be accelerated if pumped water creates bare ice patches
2071 or melt ponds rather than high-albedo snow, although Lockley et al. (2020) note that
2072 fresh snowfall would brighten the surface and that depositing ice only in winter would
2073 minimize this effect.

2074 Unforeseen ice dynamic consequences: if surface mass addition steepens the ice
2075 sheet, it could increase gravitational driving stress and flow speed at outlet glaciers
2076 (Lockley et al., 2020).

2077 **Effects on Indigenous/Local Communities**

2078 **Score:** Neutral **Confidence:** Low

2079 Antarctica has no indigenous population. Any Greenland application would require Free,
2080 Prior, and Informed Consent (FPIC) consultation with Inuit communities whose marine
2081 environments and fisheries would be directly affected by seawater extraction and
2082 infrastructure (Hopwood et al., 2025).

2083 **Ease of Reversibility**

2084 **Score:** Low **Confidence:** Medium

2085 Added ice mass would persist for thousands of years, altering glacier dynamics on very
2086 long timescales. The added ice mass could not be removed in any conceivable fashion.
2087 Even infrastructure cannot be readily removed from remote polar locations, particularly
2088 in accumulation areas, where it would need to be excavated. If the intervention
2089 steepened the ice surface and increased outlet glacier driving stress, cessation could
2090 release stored stress through accelerated flow. Environmental contamination from
2091 construction and operations would persist indefinitely. Feldmann et al. (2019)
2092 acknowledge that potential negative effects and hazards would be hard to deal with.
2093 Reversibility is low.

2094 **Likelihood of Termination Shock**

2095 **Score:** Some risk **Confidence:** Low

2096 Glaciological rebound following termination would be gradual rather than rapid, reducing
2097 but not eliminating the risk of termination shock. If deposition stopped, the added mass
2098 would remain, but the ice sheet would no longer be actively stabilized; Siegert et al.
2099 (2025) note that deposition would need to be sustained after the initial decade.
2100 Thickening glaciers also build gravitational driving stress, which may eventually
2101 overcome basal friction and lead to rapid acceleration (Lockley et al., 2020).

2102 **Suitability within Current Legal/Governance Structures**

2103 **Score:** Not possible **Confidence:** High

2104 The 2025 ATCM endorsement of a precautionary approach towards all geoengineering
2105 activities in the Antarctic, combined with the Comprehensive Environmental Evaluation
2106 requirements of Article 8 of the Madrid Protocol and the need for consensus among all
2107 29 Antarctic Treaty Consultative Parties, means that Antarctic deployment would very
2108 likely be prohibited without amendment of the Madrid Protocol (Siegert et al., 2025;
2109 Corbett & Parson, 2022).

2110 For Greenland and other Inuit homelands, any large-scale intervention would require
2111 the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN
2112 Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and
2113 set out as a minimum standard of engagement in the Inuit Circumpolar Council's

2114 Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC
2115 has no formal position on geoengineering, but considers it part of its commitment to
2116 Inuit self-determination, with the FPIC obligation extending to researchers and
2117 deployment (Crump, 2025).

2118 **Attention from Public**

2119 **Score:** Medium **Confidence:** Medium

2120 The primary scientific references are Frieler et al. (2016) and Feldmann et al. (2019),
2121 supplemented by discussion in Moore et al. (2018), Lockley et al. (2020), Wang et al.
2122 (2025), MacAyeal et al. (2024), and Siegert et al. (2025). Media coverage is occasional;
2123 commercial interest is nil. The concept is treated in the research community as a
2124 theoretical limit case illustrating the scale of the sea level problem, not a deployable
2125 intervention.

2126 **Overall Assessment**

2127 Water pumping onto ice sheets is the most resource-intensive proposed approach to
2128 surface mass balance enhancement as a sea level management strategy. The modeling
2129 of Frieler et al. (2016) and Feldmann et al. (2019) is valuable precisely because it
2130 makes the scale of the required intervention explicit.

2131 The most important constraint is that outcome reliability should be rated low. The
2132 problem is not only one of scale and energy: even if water could be delivered in
2133 sufficient quantity, its accumulation location is uncontrolled and likely counterproductive.
2134 Mass deposited near the coast is carried back to the ocean by ice flow, while water that
2135 does not freeze could pond, run off or promote hydrofracture. Added mass in
2136 dynamically unfavorable locations could increase driving stress and accelerate outlet
2137 glaciers. The intervention cannot reliably translate surface deposition into the intended
2138 glaciological stabilization.

2139 Scores are the low across virtually all criteria relevant to sea level management. The
2140 concept's scientific value relies on demonstrating that surface mass balance
2141 modification at the scale needed to stabilize ice sheets is beyond any plausible
2142 technological reach.

2143

2144 **Increasing Humidity around Glaciers and Ice Sheets**

2145 The concept of increasing atmospheric humidity around glaciers and ice sheets
2146 proposes artificially elevating moisture content in the near-surface atmosphere to
2147 enable or enhance snowfall, with the intended effect of increasing surface mass
2148 balance. The concept appears in the literature only as a passing remark in broad
2149 geoengineering reviews; no engineering design, prototype, or field trial exists.

2150 In practice, humidity augmentation is best understood as a precondition for cloud
2151 seeding rather than a standalone intervention: cloud seeding agents such as silver
2152 iodide require sufficient atmospheric moisture to act upon. The concept therefore
2153 inherits every constraint of cloud seeding (Assessment #1) and adds a further one —
2154 the need to supply the moisture itself. Without sufficient moisture, seeding agents have
2155 no supercooled cloud water to act upon and produce no precipitation.

2156 The mechanism would ostensibly work as follows: water vapor would be introduced into
2157 the near-surface atmosphere, for example via evaporative sprays, heated open-water
2158 surfaces, or other moisture-release systems, raising local humidity above the threshold
2159 required for cloud formation. The resulting clouds would then be seeded to produce
2160 snowfall, and that snowfall would augment the ice sheet's surface mass balance,
2161 partially offsetting dynamic mass loss from ice discharge. This chain encounters
2162 fundamental obstacles at almost every step, and none of its steps has been tested in a
2163 polar environment.

2164 Antarctica receives less than 50 mm of precipitation equivalent per year in its interior,
2165 and this extreme aridity reflects the very low moisture content of cold air and the
2166 isolation of the interior from oceanic moisture sources, rather than a nucleation deficit
2167 (Lockley et al., 2020). A secondary glaciological constraint, identified by Winkelmann et
2168 al. (2012), is that increased snowfall thickens and steepens ice sheets, potentially
2169 increasing gravitational driving stress and accelerating ice flow, which could counteract
2170 mass balance benefits.

2171 Where the concept appears in the literature, it is framed for Antarctica, where low
2172 humidity is the limiting condition; Lockley et al. (2020) note that much of Antarctica has
2173 extremely low humidity, with coastal regions the exception. Its applicability in Greenland
2174 is weaker still. The Greenland Ice Sheet is not moisture-starved in the way the Antarctic
2175 interior is. Added humidity would therefore not be the missing ingredient for snowfall in
2176 Greenland.

2177 **Outcome Reliability**

2178 **Score:** Uncertain **Confidence:** Low

2179 No peer-reviewed study has examined the effect of humidity augmentation on glacier or
2180 ice sheet mass balance. The proposed causal chain: moisture release to cloud

2181 formation to snowfall to ice mass gain is speculative at every step. Key scientific
2182 uncertainties include whether artificial moisture introduction could raise humidity over
2183 areas large enough to matter glaciologically; whether artificially elevated humidity would
2184 persist before being advected by katabatic winds; and whether additional snowfall would
2185 reach the portions of the ice sheet most critical for sea level. Lockley et al. (2020)
2186 suggest only that, in coastal regions where humidity is higher, cloud seeding may
2187 'conceivably' strengthen ice shelves.

2188 **Technological Readiness Level**

2189 **Score:** Low **Confidence:** High

2190 Humidity augmentation for glaciological purposes is at TRL 1 or below: no prototype,
2191 field trial, or laboratory experiment has been conducted. The concept appears in the
2192 literature only as a passing remark in broad reviews. No engineering design has been
2193 proposed for humidity augmentation at continental scale, and even cloud seeding — the
2194 next step in the chain — has never been demonstrated to produce precipitation in the
2195 interior polar environments where it would be needed; artificial snowfall has been tested
2196 in the field only on a small mountain glacier (Muz Taw Glacier, Sawir Mountains, Wang
2197 et al., 2020).

2198 **Scalability**

2199 **Score:** Low **Confidence:** High

2200 The physical scales are irreconcilable with any plausible delivery technology. Antarctica
2201 covers approximately 14 million km²; any humidity augmentation capable of
2202 meaningfully altering the atmospheric moisture budget over such an area would require
2203 energy and logistical resources entirely without precedent. Because cold polar air can
2204 hold very little water vapor, added moisture would tend to deposit as frost or be
2205 advected away by katabatic winds close to its source rather than accumulating over the
2206 ice sheet. **Scalability** is assessed as effectively nil at any glaciologically relevant scale.

2207 **Timeliness for Near-Future Effects**

2208 **Score:** Low **Confidence:** High

2209 Humidity augmentation could not be demonstrated, validated, or deployed at meaningful
2210 scale within 20 years. Establishing whether the concept is scientifically sound would
2211 require research programs that have not yet been initiated. Engineering challenges are
2212 entirely uncharacterized. Even under the most optimistic assumptions, 20 years would
2213 be insufficient to move from concept to any detectable glaciological effect.

2214 **Potential to Make a Difference in the Arctic/Northern Regions**

2215 **Score:** Low **Confidence:** Medium

2216 Arctic and sub-Arctic environments are less moisture-limited than the Antarctic interior:
2217 Greenland's coastal regions receive higher precipitation, and North Atlantic weather
2218 systems supply abundant moisture; supercooled liquid clouds occur over the Greenland
2219 Ice Sheet year-round (Shupe et al., 2013). This weakens rather than strengthens the
2220 case for humidity augmentation — where moisture is already plentiful, artificially adding
2221 more is unlikely to be the factor limiting snowfall.

2222 Lockley et al. (2020) note that surface melt accounts for approximately half of
2223 Greenland's present mass loss. The dominant drivers of Arctic ice loss remain ocean
2224 warming and surface energy balance under rising temperatures, processes not
2225 addressed by moisture augmentation. Arctic potential is low.

2226 **Potential to Make a Global Difference**

2227 **Score:** Low **Confidence:** High

2228 Humidity augmentation addresses the wrong mechanism for the glaciers most
2229 responsible for global sea level rise. Antarctic mass loss is dominated by ocean-forced
2230 dynamic discharge, which is snowfall enhancement does not directly address.

2231 Feldmann et al. (2019) calculated that stabilizing the West Antarctic Ice Sheet by
2232 surface mass deposition alone would require adding approximately 7,400 Gt of snow
2233 over 10 years — roughly a third of Antarctica's current annual snowfall each year. No
2234 moisture augmentation program could approach this magnitude.

2235 Wang et al. (2025) characterize snowfall enhancement as having a localized impact that
2236 cannot be applied on a large scale because of cost constraints and environmental
2237 issues. The fundamental constraint, that dynamic discharge is driven by ocean heat, not
2238 atmospheric precipitation deficits, cannot be resolved by any precipitation enhancement
2239 approach.

2240 **Cost to Benefit Comparison**

2241 **Score:** Prohibitive **Confidence:** Medium

2242 The energy and logistical requirements at polar scales would be extraordinary.
2243 Evaporating water requires approximately 2,260 kJ per kilogram; supplying the vapor for
2244 a 1% increase in Antarctic annual precipitation (~23 Gt) would require roughly 5×10^{19} J
2245 (~50 EJ), on the order of a month of global primary energy supply. The true requirement
2246 would be several times higher, since only a fraction of the vapor released would
2247 precipitate over the ice sheet, and a 1% precipitation increase is itself glaciologically
2248 trivial. No cost estimates exist for continental-scale humidity augmentation because the
2249 concept has never been evaluated at that scale.

2250 Brown et al. (2021) estimate the global costs of protecting coasts against sea level rise,
2251 which provide a benchmark, but humidity augmentation does not approach the scale or

2252 certainty of effect required to meaningfully contribute to avoiding those costs. Cost-
2253 benefit is prohibitive.

2254 **Likelihood of Environmental Risks**

2255 **Score:** Some risk **Confidence:** Low

2256 Humidity augmentation is rated as carrying some risk because the consequences of any
2257 large-scale moisture modification in polar environments are entirely uncharacterized.
2258 Key risk categories include: disruption of katabatic wind patterns with unanticipated
2259 feedbacks on sea ice extent, ocean circulation, and coastal ecology and unintended
2260 precipitation redistribution affecting downstream ecosystems and Southern Ocean
2261 chemistry. The score reflects the potential for unintended consequences at the scales
2262 required and the current inability to quantify or bound them.

2263 **Effects on Indigenous/Local Communities**

2264 **Score:** Negative **Confidence:** Low

2265 For Greenland and Arctic applications, Inuit and other Indigenous communities would be
2266 more likely to be affected by altered precipitation patterns, disrupted local weather, or
2267 changed water availability than to benefit from any glaciological effect.

2268 For Greenland and other Inuit homelands, any large-scale intervention would require
2269 the free, prior, and informed consent (FPIC) of Inuit, a right affirmed in the UN
2270 Declaration on the Rights of Indigenous Peoples (United Nations, 2007, Article 32) and
2271 set out as a minimum standard of engagement in the Inuit Circumpolar Council's
2272 Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC, 2022). The ICC
2273 has no formal position on geoengineering, but considers it to fall under its commitment
2274 to Inuit self-determination, with the FPIC obligation extending to researchers as well as
2275 to deployment (Crump, 2025). Indigenous communities depend on predictable weather,
2276 water availability, and ecosystem services that could be disrupted by any precipitation
2277 modification activities. The negative rating reflects the more likely direction of effect; its
2278 magnitude remains highly uncertain and community dependent.

2279 **Ease of Reversibility**

2280 **Score:** High **Confidence:** High

2281 Atmospheric moisture interventions leave no persistent physical structures to remove
2282 and no lasting changes to the glaciological system beyond any snow already deposited.
2283 Once operations cease, added moisture disperses and the atmosphere returns to
2284 background conditions within days.

2285 Reversibility is easy, though this partly reflects that the intervention is unlikely to
2286 produce any lasting effect.

2287 **Likelihood of Termination Shock**

2288 **Score:** Low risk **Confidence:** High

2289 Ceasing humidity augmentation operations produces no abrupt rebound in the climate
2290 or glaciological system. There is no sustained forcing.

2291 The low termination risk is almost entirely attributable to the intervention's likely
2292 negligible efficacy.

2293 **Suitability within Current Legal/Governance Structures**

2294 **Score:** Not possible **Confidence:** High

2295 Antarctic humidity augmentation operations would constitute geoengineering activities
2296 subject to the Madrid Protocol and to the 2025 ATCM endorsement of a precautionary
2297 approach towards all geoengineering activities in the Antarctic (Siegert et al., 2025).
2298 Even operations characterized as research would require a Comprehensive
2299 Environmental Evaluation and Antarctic Treaty Consultative Party consensus, which the
2300 current governance environment does not support. Research operations with more than
2301 a minor or transitory impact would require a Comprehensive Environmental Evaluation,
2302 and Corbett & Parson (2022) conclude that the Madrid Protocol would very likely
2303 prohibit operational interventions without amendment.

2304 For Greenland and the Arctic, national authorizations would be required, and
2305 transboundary precipitation effects could engage international atmospheric liability
2306 frameworks. Operations in Greenland would require authorization from the Greenland
2307 Government with FPIC obligations to Inuit communities (United Nations, 2007; ICC,
2308 2022). In practice, governance obstacles are prohibitive at any scale approaching
2309 glaciological relevance.

2310 **Attention from the Public**

2311 **Score:** Low **Confidence:** High

2312 Increasing humidity around glaciers as a standalone intervention concept receives
2313 essentially no dedicated attention in the peer-reviewed literature, public media, or from
2314 industry. It appears only as a brief contextual remark in a handful of broad
2315 geoengineering reviews. The sole substantive mention is a qualifying sentence in
2316 Lockley et al. (2020), noting that cloud seeding in Antarctica 'would rely on appropriate
2317 temperatures and humidity levels; much of Antarctica has extremely low humidity.' No
2318 dedicated peer-reviewed paper, conference session, or research program addresses
2319 this concept.

2320 **Overall Assessment**

Humidity augmentation does not offer a credible pathway to meaningful glaciological intervention or sea level management. It is best understood as a precursor to cloud seeding rather than an independent intervention, and so inherits every limitation identified in Assessment 1 while adding the problem of supplying the moisture itself. It faces a basic paradox: added moisture would be needed only where it is least feasible to supply (the cold, dry Antarctic interior) and is unnecessary where moisture is already available, at the Antarctic coast and over Greenland.

The most basic obstacle is the atmospheric condition of the potential target areas. Antarctica is an extreme polar desert, and the moisture deficit is not a technological problem but a consequence of the large-scale atmospheric circulation of the polar cell. Dry air descends over the Antarctic plateau, preventing the accumulation of moisture needed for precipitation. No realistic moisture-introduction technology could alter this circulation pattern at the scales required. At coastal margins — where moisture availability is less limiting — the primary drivers of ice loss are oceanographic, not atmospheric.

For Greenland and Arctic mountain glaciers, the concept is marginally more atmospherically plausible — moisture is more abundant, and conventional cloud seeding has demonstrated modest effects in some mid-latitude contexts. But the glaciological relevance remains low: about half of Greenland's mass loss is from surface melt and the rest from ice discharge (Lockley et al., 2020), neither of which is limited by atmospheric moisture, and mountain glaciers' total sea level contribution, while significant, cannot be meaningfully addressed through precipitation enhancement alone.

The two criteria where humidity augmentation scores favorably — reversibility and termination shock — are favorable because the intervention is likely to do very little. Its environmental risks, by contrast, are uncharacterized. The consequences of large-scale moisture modification in polar environments, including feedbacks on katabatic wind systems and Southern Ocean circulation, are entirely uncharacterized.

Because no peer-reviewed study has examined humidity augmentation as a glaciological intervention, and the concept appears in the literature only in passing as an implicit prerequisite of cloud seeding, this conclusion rests on what is known about polar atmospheric conditions, the physics of moisture transport, and the broader evidence base on cloud seeding and precipitation enhancement, rather than on any evaluation of the technique itself.

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