

UArctic Climate Interventions
Draft Sea Ice Assessment Report for Review¹
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Note:

In addition to the eight climate interventions categorized as relating to sea ice in the original rapid assessment, the Sea Ice team also included Snowfall Enhancement from the atmosphere category as being particularly relevant to the protection of sea ice. They also added four new interventions: Reinforcing sea ice arches by sea ice thickening, Wood ice seed, Sea ice arches with artificial structures, and Sea ice generation by icebreaking in winter.

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

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Draft for Review

Iceberg management

Overall assessment: The sea ice and iceberg management concept, proposed by Veli Albert Kallio in a series of posts to the Geoengineering Google Group in 2010, appears to have been largely abandoned since its initial suggestion, with no peer-reviewed follow-up, dedicated engineering studies, or field experiments reported in the scientific literature. The idea must therefore be regarded as purely conceptual and speculative at the current stage. Without more evidence, our ability to evaluate the approach is extremely limited.

Even at the conceptual level, the physical feasibility of the approach was highly uncertain. The kinetic energy and momentum of drifting sea ice masses and icebergs impose enormous mechanical forces on any structure placed in their path, raising serious doubts about whether cables, levees, or anchoring systems could withstand such loads in practice. These engineering challenges were acknowledged in the original discussion thread and were never resolved.

Beyond feasibility, deployment in remote Arctic straits would be logistically demanding and prohibitively costly, given the need for specialised marine infrastructure, seafloor anchoring, and continuous monitoring in one of the world's most inaccessible and harsh environments. Scalability was inherently low, as the approach was confined to glacier calving area or/and shallow coastal and shelf areas, excluding the vast majority of the Arctic Ocean. Taken together, these limitations suggest that the concept, while intellectually interesting as a localised intervention at strategic choke points, faced fundamental barriers that would need to be addressed before it could be considered a viable climate intervention.

Issue being addressed

With rising Arctic temperatures, there have been major changes in iceberg production rates of marine terminating glaciers. These icebergs drift into warmer sea waters where they will slowly melt.

Description of the technology/ measure

In a series of posts to the Geoengineering Google Group in 2010, Veli Albert Kallio suggested the possibility that 'suspension cabling' could hold ice in place and prevent it moving into the warm waters (Kallio 2010). These cables would potentially sink or be removable. The original post suggested placing the cables in the Robeson Channel between Canada and Greenland. Several responses remarked it might be worthwhile to look into the use of such cables to reduce the outflow rate of ice in other areas. This approach has the advantage of a limited environmental footprint, as it aims to physically retain the cryosphere in place and prevent enhanced melting at lower latitudes. However, its feasibility has not been demonstrated, particularly regarding the ability to withstand the kinetic energy of massive ice masses driven by the powerful forces of ocean currents and wind. Cable resistance and anchoring both in the ice and at the seafloor, in particular represent major engineering

challenges. An alternative strategy would be to direct iceberg drift so as to deliberately ground them at shallow sites, thereby forming natural barriers to ice outflow. The setup would also raise navigation safety concerns in the targeted area. While focusing on the Robeson Channel is geographically justified given its narrow geometry, this also underscores that the approach is inherently site-specific, which raises broader questions about its scalability to more open and exposed Arctic regions.

Technological readiness

Score: Low **Confidence:** High

The plan has not been explored seriously in the scientific literature. It has many drawbacks related to the dynamics of the cables.

Scalability

Score: Low **Confidence:** High

The scalability of the technique is fundamentally limited to iceberg calving zones and by the need to anchor structures to the seabed or shore, confining realistic deployment to shallow coastal and shelf areas and excluding the vast majority of the deep Arctic Ocean. As the aerial extent of deployed structures increases, the mechanical stresses imposed by sea ice drift and currents would increase considerably, posing inherent structural limits to any upscaling effort.

Timeliness for near-future effects

Score: Medium **Confidence:** High

The concept has not been seriously explored since its initial proposal, and no dedicated engineering studies or field trials have been reported. Given the low technological readiness and the substantial unresolved questions surrounding cable deployment, mechanical integrity, and effectiveness in dynamic Arctic conditions, any near-future contribution to Arctic sea ice recovery appears unlikely. Localised pilot experiments in shallow coastal environments could in principle be envisaged within the next decade, but climatically meaningful effects remain distant.

Potential to make a difference in Northern + Arctic

Score: Medium **Confidence:** High

Confinement to shallow coastal and shelf areas limits the regional impact of the approach, with any effect on the overall Arctic sea ice budget remaining modest and highly localised. An exception may be targeted deployment at strategic choke points such as sea-ice arch formation zones, where a localised intervention could extend landfast ice duration and yield a disproportionately large Arctic-scale benefit.

117 **Potential to make a global difference**

118 **Score:** Low **Confidence:** High

119 This would only be applicable to specific iceberg producing regions and within
120 shallow waters and narrow straits, limiting the large scale impact

121 **Cost - Benefit**

122 **Score:** Prohibitive **Confidence:** High

123 Little information is available on the costs of this approach, as it has not been
124 seriously developed beyond its initial conceptual proposal. However, deployment is
125 very likely to be costly, given the considerable forces that would need to be
126 contained — including the kinetic energy of drifting sea ice masses, icebergs, and
127 ocean currents — and the remoteness and inaccessibility of the target sites in Arctic
128 straits, which would make installation, maintenance, and monitoring of any cable or
129 levee system logistically demanding and expensive.

130 **Likelihood of environmental risks**

131 **Score:** Some risk **Confidence:** Medium

132 The original post already encouraged further research into the environmental effects
133 of this measure, and a thorough assessment remains difficult in the absence of
134 detailed information on the design, materials, and mode of deployment envisaged.
135 Nevertheless, the deployment of cables, ropes, or levees on the seabed and in the
136 water column would inevitably introduce physical structures into the marine
137 environment, carrying potential ecological impacts including entanglement risks for
138 marine mammals and fish, and disturbance to benthic habitats. At the same
139 time, such structures could generate localised positive ecological effects, by creating
140 new hard substrate that increases local productivity, attracts higher trophic level
141 species such as fish, provides habitat for juvenile fish and invertebrates, and offers
142 attachment surfaces for sessile organisms. Overall, the environmental risk is
143 assessed as moderate, reflecting the balance between these potential negative and
144 positive effects in a sensitive Arctic marine environment.

145 **Effects on local/ indigenous communities**

146 **Score:** Neutral **Confidence:** Low

147 There is a lack of information to assess the impact on local communities. However,
148 promoting sea ice stabilisation support safe surface travel could be beneficial to
149 hunting and local transportation in coastal communities.

150 **Ease of reversibility**

151 **Score:** High (easy) **Confidence:** Low

152 The intervention is in principle reversible through the physical retrieval of the
153 deployed cables or levees. However, the practical difficulty of removing such
154 structures after potential entanglement with sea ice, burial in seafloor sediments, or

structural damage under ice forces is difficult to assess given the limited information available on the deployment method. Any positive ecological effects arising from the creation of hard substrate habitat would also take time to reverse following removal. Reversibility is therefore considered feasible in principle, but operationally uncertain.

Risk of termination shock

Score: Low Risk **Confidence:** High

The risk of termination shock is low. The intervention does not generate a sustained climatic forcing whose abrupt cessation would trigger a rapid compensatory climatic response. Removing or ceasing the maintenance of the cable or levee structures would simply allow sea ice export to return progressively to its pre-intervention levels, without abrupt transition. Any residual ecological effects associated with the presence of the structures — such as the persistence of colonised hard substrate — would also dissipate gradually over time following removal.

Suitability within current legal/ governance structures

Score: Challenging **Confidence:** High

Such an intervention would likely affect regional oceanographic conditions and alter the extent of the landfast ice zone. Furthermore, the cable infrastructure would pose significant navigational hazards in the surrounding waters, requiring dedicated exclusion zones.

Amount of attention in scientific journals and public media and currently ongoing research programs

Score: Low **Confidence:** High

This idea has received very little attention, either in the media or in research.

Modular iceberg creation by submersibles

Overall assessment: The idea is to freshen seawater and freeze it based on the higher melting point of fresh water (0°C) compared to normal ocean water (−2°C). Use of this method is questionable in natural conditions in the Arctic due to technical requirements and to unsolved transfer of latent heat out of the system. This method is not considered viable.

Issue being addressed

Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether with major effects on local communities and ecosystems. The disappearance of the reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.

Description of the technology/ measure

In 2019, an Indonesian design team came up with the idea of a submersible device that could take in sea water, desalinate it, and then have it freeze into a solid block they called a “new ice baby” (Griffiths, 2019). Although the idea received a second prize in a 2019 international design competition, and the related video gained much media attention, it is not clear what exactly the designers tried to achieve with their device. Most likely these modular icebergs would replace Arctic sea ice, but it is not specified how this would be done. In the project’s description, the designers explain they see this as an analogue to tree planting programs in tropical forests, without stating how this would have climate positive effects. Moreover, they confuse the Arctic and Antarctic several times, and seem to be unaware of the basics of sea ice physics. In particular, the analogue with tree planting is incomplete, and it is not clear how to remove the latent heat released in freezing out from the system.

Technological readiness

Score: Low **Confidence:** Low

This idea only exists on a drawing board, and no serious research has been done.

Scalability

Score: Medium **Confidence:** Low

Impact is proportional to the produced number of icebergs.

Timeliness for near-future effects

Score: Low **Confidence:** High

The concept exists solely as a design proposal and has not been developed beyond a media-covered competition entry. No engineering studies, prototypes, or scientific research have been conducted. Given the fundamental unresolved challenges — including the energy requirements for freezing seawater at scale, the removal of

219 latent heat in polar conditions, and the need for thousands of devices — any near-
220 future contribution to Arctic sea ice recovery is considered extremely unlikely.

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

222 **Score:** Low **Confidence:** Low

223 Would need a large number of icebergs. Even under optimistic assumptions, the
224 number of submersible devices required to produce a climatically meaningful volume
225 of ice would be enormous — far beyond any realistic deployment capacity.
226 According to the design proposal, each device produces one hexagonal ice block of
227 approximately 2,027 m³ per month (Designboom, 2019), whereas the Arctic loses
228 sea ice at rates of tens of thousands of km³ per year. The approach is therefore
229 assessed as having negligible potential to make a meaningful difference at the
230 Northern and Arctic scale.

231 **Potential to make a global difference**

232 **Score:** Low **Confidence:** High

233 Along with the slow and costly production of the ice, the potential to make a global
234 difference is low.

235 **Cost - Benefit**

236 **Score:** Prohibitive **Confidence:** High

237 Thousands of such devices would be needed, generating equal concerns about
238 costs, sustainability, and possible ways to transport. Furthermore, these
239 submersibles would require energy, and although the design features solar panels, it
240 is not sure how these would work.

241 **Likelihood of environmental risks**

242 **Score:** Low risk **Confidence:** Low

243 Icebergs would be a new risk for shipping. But the ecological footprint is likely to be
244 low.

245 **Effects on local/ indigenous communities**

246 **Score:** Neutral **Confidence:** Low

247 Icebergs could disturb fishing and hunting.

248 **Ease of reversibility**

249 **Score:** High (easy) **Confidence:** Low

250 “Icebergs” would still be left, but compared to other climate intervention, there is no
251 structure to be removed, or material disseminated over large area

252 **Risk of termination shock**

253 **Score:** Low risk **Confidence:** Low

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

255 **Score:** Challenging **Confidence:** Low

256 The deliberate creation of artificial icebergs would introduce new navigational
257 hazards in Arctic waters, although it should be noted that natural icebergs already
258 represent an established hazard in the same regions.

259 **Amount of attention in scientific journals and public media and currently**
260 **ongoing research programs**

261 **Score:** Low **Confidence:** High

262 Although the project has not been developed further, it is still relatively frequently
263 mentioned in blog posts and less critical news media.

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Increasing albedo through sea ice thickening

Overall assessment: Sea ice thickening with water pumped from under the ice is common across the Arctic to construct roads, airstrips, and drill platforms. The method is applicable during the cold season. Theoretically, artificially thickened ice could prolong its seasonal persistence, increase net albedo, thereby slowing planetary warming. Preliminary field testing shows promise, but the results are not wholly consistent. Additional research is needed to demonstrate substantial effects on ice and atmospheric temperature, technical readiness, scalability, and environmental effects. As with other proposed sea ice interventions, governance concerns are yet to be adequately addressed.

Issue being addressed

The decrease in albedo of the Arctic Ocean as a consequence of diminishing sea ice has increased global warming in recent decades by about 25% of the warming due to greenhouse gases emissions (Pistone et al. 2014). Including the effect of diminishing terrestrial snow cover increases the contribution of reduced albedo to about 44% of the warming due to fossil fuel emissions (Marcianesi et al. 2021).

Desch et al. (2017) proposed lengthening the seasonal duration of sea ice (and albedo) by flooding the surface with water pumped from below. They hoped to provoke discussions of the feasibility as well as the “morality and ethics and politics of the approach”. Modeling studies suggested that flooding snow on sea ice would be most effective at thickening Arctic sea ice “when flooding begins early in the sea ice growth season” (Pauling and Bitz 2021). In 2024, two teams began field tests of thickening Arctic sea ice. Arctic Reflections flooded ice in [Svalbard](#) (2024), [Newfoundland](#) (2025), and [Baffin Bay](#) (2026) (Hammer et al. 2026) while [Real Ice](#) conducted similar experiments in Cambridge Bay in 2024, 2025, and 2026 (Blanchard-Wrigglesworth et al. 2026).

Description of the technology/ measure

Thickening sea ice could slow its decline, and the increase in net albedo would slow planetary warming. Desch *et al.* (2017) suggested pumping sea water on top of already existing ice during winter and letting it freeze. Thickening would extend the life of sea ice later into the summer. Desch *et al.* (2017) suggested a large number of floating wind-powered pumps could be deployed for thickening.

Technological readiness

Score: Medium

Confidence: Medium

Pumping water from under sea ice in the winter is a proven method for building ice roads and drilling platforms (C-CORE 2005; Andreeva and Sharapov 2023; Daly et

al. 2023) which persist longer than the surrounding ice. To increase albedo, Desch *et al.* (2017) envisioned many floating wind-powered pumps.

Current experiments are using gasoline (Arctic Reflections) and electric powered pumps (Real Ice) on the surface drawing water through holes drilled through the ice. In 2026, Real Ice successfully tested an under-ice drone, powered by hydrogen fuel cells, that can penetrate the ice and pump water from below. Both of the current field campaigns are making progress demonstrating technical feasibilities at local scale. Both flood the ice with streams of water emanating just above the surface, but in ice road and drill platform constructions, spraying of ice is deemed more efficient (C-CORE 2005; Andreeva and Sharapov 2023). Real Ice and Arctic Reflections both reported substantially thicker ice in their test areas.

An additional technical challenge, particularly relevant for unattended autonomous systems, is pipe freezing: any interruption in power supply or seawater flow will cause residual water in the pipes to freeze rapidly under Arctic ambient temperatures, rendering the device inoperable. To date the Real Ice and Arctic Reflections tests have largely been confined to stable shore fast ice, and technical challenges likely will be much greater in dynamic pack ice. We assess technical readiness to be medium but with the potential to rapidly advance.

Scalability

Score: Medium

Confidence: High

Scalability remains to be determined, although ice drilling and pumping from below the ice—in early development—could substantially increase the prospects for large-scale efforts.

Most of the tests have been carried out on landfast ice, which is attached to the coastline or grounded on the seafloor. Landfast ice forms a continuous surface over which pumping equipment can operate effectively and water can spread across large contiguous areas. Pack ice, by contrast, is composed of discrete drifting floes separated by open leads. Because pumped water will drain rapidly through these leads rather than spreading across adjacent floes, the effective reach of a single pump is fundamentally constrained by the lateral extent of the individual floe on which it is deployed. Consequently, scaling up sea ice thickening in pack ice conditions would require either the use of under-ice pumps on autonomous drones or the deployment of an independent pumping device on each individual floe, with the number of devices scaling directly with the number of floes to be treated.

This distinction has major implications for scalability. Arctic landfast ice reaches a maximum annual extent of approximately 1.8 million km² — roughly 12% of total Arctic wintertime sea ice cover — and is concentrated along Eurasian and Canadian

Arctic shelves (Yu et al. 2013). The remaining ~88% of Arctic sea ice consists of drifting pack ice, which is precisely the ice type most relevant to albedo restoration and summer ice preservation on a climatically meaningful scale. The logistical and economic constraints associated with deploying and maintaining pumping devices across millions of fragmented, drifting floes represent a fundamental scalability challenge that has yet to be addressed.

If on-ice pumps were deployed, their retrieval would be logistically demanding and technically challenging at scale. If left in place, the devices would need to be positively buoyant to prevent polluting the seabed with foreign materials in violation of maritime and environmental frameworks. Under-ice autonomous vehicles, such as those currently being developed by Real Ice, would partially circumvent this problem by operating below the ice and being retrievable.

In the meantime, we assess scalability to be medium.

Timeliness for near-future effects

Score: Medium

Confidence: Medium

Timeliness for near-future effects will depend greatly on acceleration of testing and development over much broader areas, given the limitations and issues mentioned above, and the successful development of abilities to drill and pump from below the ice. We assess timeliness to be medium.

Potential to make a difference in Northern + Arctic

Score: High

Confidence: Medium

A modeling effort suggested slowing the loss of Arctic sea ice would result in a global forcing of -0.08 W/m^2 for the period of 2061–2100 (Zampieri and Goessling (2019). Both Zampieri and Goessling (2019) and Pauling and Bitz (2021) point out that, at best, thickening sea ice would likely only delay the eventual disappearance of Arctic summer ice. Such a delay, however, could critically increase the time to reduce greenhouse gas concentrations in the atmosphere. Thus, we assess the potential to make a difference in Northern and Arctic environments to be high.

Potential to make a global difference

Score: Low

Confidence: High

If more Arctic sea ice could actually be preserved, ice thickening would have some effect on the global energy budget. A model study found a global -0.08 W/m^2 forcing effect for the period of 2061–2100 (Zampieri and Goessling 2019). Both Zampieri and Goessling (2019) and Pauling and Bitz (2021), however, also find that although certain pumping strategies might lead to better results, they would only delay the eventual disappearance of Arctic summer ice under expected warming scenarios. In

377 Cambridge Bay, artificially thickened sea ice was still 40 cm thick in July when
378 control area ice had melted away (Blanchard-Wrigglesworth et al. 2026). In contrast,
379 ice artificially thickened in Vallunden Lagoon, Svalbard in 2024 did not persist longer
380 than control ice, a result that may have been particular to the conditions in Vallunden
381 Lagoon (Hammer et al. 2026).

382 **Cost - Benefit**

383 **Score:** Moderate **Confidence:** Low

384 Desch *et al.* (2017) give a rough estimate of \$50 billion per year to increase ice
385 thickness by one metre over 10% of the Arctic, The accuracy of this estimate,
386 however, is highly uncertain as there are many unknowns. For example, how the
387 pumps would behave in the Arctic, what will be their footprint in fragmented ice
388 cover, how they could be maintained and repaired, and ultimately how much carbon
389 would be emitted in the pumping operations.

390 It should, however, be noted that Hao *et al.* (2023) estimate that the melting of the
391 sea ice would cost the world an average of 6.7–13.3 trillion USD annually over the
392 period 2020 to 2100, when the costs of the forcing effects of the ice are calculated in
393 terms of equivalent costs of the forcing that is the result of GHG emissions.

394 **Likelihood of environmental risks**

395 **Score:** Some risk **Confidence:** Medium

396 Miller *et al.* (2020) note that this kind of thickening could affect Arctic marine
397 biochemistry in multiple ways. The pumping process would, for example, release
398 aerosols which would alter atmospheric chemistry, might increase or decrease
399 temperatures, and “could have myriad contrasting impacts on the Arctic
400 atmosphere”. They also note that this scheme might affect the availability of light for
401 photosynthesising algae under the ice, thereby reducing marine productivity, or
402 reduce algae production directly by removing shallow, algae-rich waters, and
403 pumping them on top of the ice. Any impacts on sub-ice algae would depend on the
404 seasonal timing of pumping, which may well be most effective in dark winter months
405 when algal production is minimal.

406 Organisms living on, in, and under sea ice likely would be affected by physical
407 changes in flooded ice (Ehrlich et al. 2020; Lund-Hansen et al. 2025). Pumping
408 would decrease light transmittance in snow-free areas but increase in snow areas.
409 Albedo would respond in the opposite manner. Real Ice has just begun to collect
410 data in 2026 on the impact on ice flora and fauna.

411 In such a harsh and dynamic environment, on-ice pumps, if used, would need to
412 float and be retrieved so they would not end up on the seafloor. Under-ice drone
413 pumps would minimize that concern.

414 Blanchard-Wrigglesworth et al. (2026) note that flooding snow cover on sea ice could
415 be deleterious to mammals who depend on it for birthing and nursing sites. In

416 particular, polar bears and ringed seals (Kelly 2001; Kelly et al. 2010a, b; Regehr et
417 al. 2007; Molnar et al. 2020).

418 Furthermore, if surface pumps were to be used, the distribution and maintenance of
419 the pumps could be a major source of Arctic GHG emissions, and the pumps would
420 have to be made out of non-toxic materials. Real Ice, however, has demonstrated
421 the ability to use battery-powered pumps, and they have developed and successfully
422 tested pumping from an under-ice drone.

423 **Effects on local/ indigenous communities**

424 **Score:** Unknown **Confidence:** High

425 The worries about the potential biochemical effects of sea ice thickening expressed
426 by Miller *et al.* (2020) might have significant effects on the livelihoods of local and
427 indigenous communities who rely on hunting and fishing. Desch *et al.* (2017)
428 suggested that the pumps might be maintained by local and indigenous
429 communities, thereby providing social co-benefits, but it is unclear if this could
430 actually be done in practice.

431 Prolonging the duration of ice thick enough to support safe surface travel could be
432 beneficial to hunting and local transportation in many coastal communities.

433 Concerns about effects on Indigenous and other local communities highlight an
434 essential need to facilitate their involvement in considering these approaches.

435 **Ease of reversibility**

436 **Score:** Medium **Confidence:** High

437 Surface pumps could probably be removed at some cost. Under-ice drone pumps
438 would minimize that concern.

439 **Likelihood of termination shock**

440 **Score:** Low risk **Confidence:** Medium

441 Successful thickening could restore ice conditions in 1 to 4 years. It is difficult to
442 envision a strong termination shock.

443 If on-ice pumps were left in place, the associated pollution released in the
444 environment during ice break-up/melt will remain for a long period. Their impact is
445 still to be assessed, but will relate to the type and number of pumps deployed.

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

447 **Score:** Challenging **Confidence:** Medium

448 Although it is not clear how the deployment of such pumps would be governed on
449 the High Seas, the five Arctic coastal states would likely be able to deploy such
450 pumps if they wanted to within their Exclusive Economic Zones (Moore *et al.* 2020).
451 Both Argüello and Johansson (2022) and Bennett *et al.* (2022) have recently called

452 for discussions on security, ethical, and governance issues around sea ice
453 thickening and other Arctic ice management techniques.

454 **Amount of attention in scientific journals and public media and currently**
455 **ongoing research programs**

456 **Score:** Medium **Confidence:** High

457 Sea ice thickening has been featured in popular media (See for example the
458 prominent reports of Desch' 2017, Luhn, 2025, in Scientific American, McKie, 2025,
459 in The Guardian and by Bukszpan, 2017 in CNBC). There has been limited
460 academic coverage of this idea besides the studies already cited here, although
461 there are government and industry reports on the regular practice of sea ice
462 thickening for the construction of ice roads, airstrips, and drill platforms (C-CORE
463 2005; Andreeva and Sharapov 2023; Daly et al. 2023). Moreover, there are at least
464 two well-funded projects continuing modeling and field testing of this approach.

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Reinforcing sea ice arches by sea ice thickening

Sea ice arches are natural structures that form seasonally in narrow Arctic straits — most notably the Nares Strait between Ellesmere Island and Greenland — and act as gatekeepers that block the southward export of thick, multi-year ice. Climate change is destabilizing these arches: their average seasonal duration in the Nares Strait has shortened from 177 to 128 days over the past four decades, and years without arch formation are becoming more frequent, leading to doubled ice export fluxes.

It has been proposed that reinforcing naturally forming ice arches at well determined locations by using the method “increasing albedo through sea ice thickening”, i.e. pumping or spraying seawater onto their structure, thickening the ice and extending their mechanical stability through the melt season (see Sea Ice Thickening sections below).

The cost-benefit profile of this intervention is potentially more favourable than that of broad-area sea ice thickening approaches. By concentrating the application of sea ice thickening techniques at a small number of strategic geographic choke points — rather than across vast expanses of the Arctic Ocean — the total surface area requiring treatment is reduced by several orders of magnitude, with a corresponding reduction in the number of pumping units, fuel consumption, logistical support, and operational costs. At the same time, the potential climate benefit is disproportionately large relative to the treated area: reinforcing an arch at a single location such as the Nares Strait could prevent the annual export of approximately 100,000 km² of thick multi-year ice, yielding an Arctic-scale impact at a fraction of the infrastructure cost of basin-wide interventions. This targeted, high-leverage geometry is the primary argument in favour of a favourable cost-benefit assessment, albeit contingent on the intervention proving structurally and mechanically feasible.

Issue being addressed

Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker open water during Arctic summers, further accelerating warming through the ice-albedo feedback. The decrease in albedo of the Arctic Ocean as a consequence of diminishing sea ice has increased global warming in recent decades by about 25% of the warming due to greenhouse gas emissions (Pistone et al. 2014). Including the effect of diminishing terrestrial snow cover increases the contribution of reduced albedo to about 44% of the warming due to fossil fuel emissions (Marcianesi et al. 2021).

A key but often overlooked driver of Arctic sea ice loss is the lateral export of sea ice through narrow Arctic straits. In the Nares Strait alone, the absence of a natural ice

arch — which in recent decades has become more frequent as ice thins — allows approximately 100,000 km² of thick, multi-year ice to be flushed southward into Baffin Bay each year (Moore et al. 2021). This exported ice is irretrievably lost to the Arctic system, representing a net drain on the oldest sea ice class. As climate change continues to thin and weaken the natural ice arches that seasonally block these export pathways, their protective function is diminishing, compounding the loss driven by in-situ melting.

Description of the technology/ measure

It has been proposed to reinforce naturally forming ice arches by applying the sea ice thickening method (Desch et al. 2017) at the arch location: seawater is pumped or sprayed onto the arch structure during winter, where it freezes and increases ice thickness and compressive strength, thereby extending the arch's mechanical stability and seasonal duration.

Technological readiness

Score: Medium **Confidence:** Medium

The ice thickening technological readiness is 2. (See *Increasing Albedo Through Sea Ice Thickening* section below).

Scalability

Score: High **Confidence:** High

The core rationale of the sea ice arch intervention is to overcome the scalability limitation inherent to broad-area sea ice thickening approaches such as those proposed by Desch et al. (2017) or currently tested by Real Ice and Arctic Reflections. Rather than attempting to thicken ice across millions of square kilometres of Arctic Ocean — a task requiring an impractical number of pumping devices — the sea ice arch approach concentrates the intervention at a small number of geographic choke points where the impact per unit of effort is maximised. The Nares Strait, with a width of only ~35 km, controls the export of approximately 100,000 km² (Moore et al. 2021) of multi-year ice per year when the arch is absent; reinforcing or recreating an arch at this single location could thus yield an Arctic-scale benefit at a fraction of the infrastructure cost of distributed thickening. This targeted, high-leverage geometry is the primary argument in favour of a high scalability score, albeit contingent on the intervention proving structurally and mechanically feasible.

Timeliness for near-future effects

Score: Medium **Confidence:** Medium

Timeliness for near-future effects will depend greatly on acceleration of testing and development over much broader areas, given the limitations and issues mentioned

546 above, and the successful development of abilities to drill and pump from below the
547 ice. We assess timeliness to be medium.

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

549 **Score:** High **Confidence:** Medium

550 A modeling effort suggested slowing the loss of Arctic sea ice would result in a global
551 forcing of -0.08 W/m² for the period of 2061–2100 (Zampieri and Goessling (2019)).
552 Both Zampieri and Goessling (2019) and Pauling and Bitz (2021) point out that, at
553 best, thickening sea ice would likely only delay the eventual disappearance of Arctic
554 summer ice. Such a delay, however, could critically increase the time to reduce
555 greenhouse gas concentrations in the atmosphere. Thus, we assess the potential to
556 make a difference in Northern—including Arctic—environments to be high.

557 **Potential to make a global difference**

558 **Score:** Low **Confidence:** High

559 If more Arctic sea ice could actually be preserved, ice thickening would have some
560 effect on the global energy budget. A model study found a global - 0.08 W/m² forcing
561 effect for the period of 2061–2100 (Zampieri and Goessling 2019). Both Zampieri
562 and Goessling (2019) and Pauling and Bitz (2021), however, also find that although
563 certain pumping strategies might lead to better results, they would only delay the
564 eventual disappearance of Arctic summer ice under expected warming scenarios. In
565 Cambridge Bay, artificially thickened sea ice was still 40 cm thick in July when
566 control area ice had melted away (Blanchard-Wrigglesworth et al. 2026). In contrast,
567 ice artificially thickened in Vallunden Lagoon, Svalbard in 2024 did not persist longer
568 than control ice, a result that may have been particular to the conditions in Vallunden
569 Lagoon (Hammer et al. 2026).

570 **Cost - Benefit**

571 **Score:** Cost-effective **Confidence:** Medium

572 By using the “Sea ice thickening” technique upon a limited targeted area, the costs of
573 the technique will dramatically reduce the cost of the deployment and could have a
574 disproportionate impact compared to the large-scale “increasing albedo through sea
575 ice thickening” method.

576 **Likelihood of environmental risks**

577 **Score:** Some risk **Confidence:** Medium

578 Miller *et al.* (2020) note that this kind of thickening could affect Arctic marine
579 biochemistry in multiple ways. The pumping process would, for example, release
580 aerosols which would alter atmospheric chemistry, might increase or decrease
581 temperatures, and “could have myriad contrasting impacts on the Arctic
582 atmosphere”. They also note that this scheme might affect the availability of light for

583 photosynthesising algae under the ice, thereby reducing marine productivity, or
584 reduce algae production directly by removing shallow, algae-rich waters, and
585 pumping them on top of the ice.

586 Organisms living on, in, and under sea ice likely would be affected by physical
587 changes in flooded ice (Ehrlich et al. 2020; Lund-Hansen et al. 2025). Pumping
588 would decrease light transmittance in snow-free areas but increase in snow areas.
589 Albedo would respond in the opposite manner. Real Ice has just begun to collect
590 data in 2026 on the impact on ice flora and fauna.

591 In such a harsh and dynamic environment, on-ice pumps, if used, would need to
592 float and be retrieved so they would not end up on the seafloor. Under-ice drone
593 pumps would minimize that concern.

594 Blanchard-Wrigglesworth et al. (2026): note that flooding snow cover on sea ice
595 could be deleterious to mammals who depend on it for birthing and nursing sites. In
596 particular, polar bears and ringed seals (Kelly 2001; Kelly et al. 2010a, b; Regehr et
597 al. 2007; Molnar et al. 2020).

598 Furthermore, if surface pumps were to be used, the distribution and maintenance of
599 the pumps could be a major source of Arctic GHG emissions, and the pumps would
600 have to be made out of non-toxic materials. Real Ice, however, has demonstrated
601 the ability to use battery-powered pumps, and they have developed and successfully
602 tested pumping from an under-ice drone.

603 **Effects on local/ indigenous communities**

604 **Score:** Unknown **Confidence:** High

605 The worries about the potential biochemical effects of sea ice thickening expressed
606 by Miller *et al.* (2020) might have significant effects on the livelihoods of local and
607 indigenous communities who rely on hunting and fishing. Desch *et al.* (2017)
608 suggested that the pumps might be maintained by local and indigenous
609 communities, thereby providing social co-benefits, but it is unclear if this could
610 actually be done in practice.

611 Prolonging the duration of ice thick enough to support safe surface travel could be
612 beneficial to hunting and local transportation in many coastal communities.

613 Concerns about effects on Indigenous and other local communities highlight an
614 essential need to facilitate their involvement in considering these approaches.

615 **Ease of reversibility**

616 **Score:** Medium **Confidence:** High

617 Surface pumps could probably be removed at some cost. Under-ice drone pumps
618 would minimize that concern.

619 **Risk of termination shock**

620 **Score:** Low risk **Confidence:** Medium

621 Successful thickening could restore ice conditions in 1 to 4 years. It is difficult to
622 envision a strong termination shock.

623 If on-ice pumps were left in place, the associated pollution released in the
624 environment during ice break-up/melt will remain for a long period. Their impact is
625 still to be assessed, but will relate to the type and number of pumps deployed.

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

627 **Score:** Challenging **Confidence:** Medium

628 Although it is not clear how the deployment of such pumps would be governed on
629 the High Seas, the five Arctic coastal states would likely be able to deploy such
630 pumps if they wanted to within their Exclusive Economic Zones (Moore *et al.* 2020).
631 Both Argüello and Johansson (2022) and Bennett *et al.* (2022) have recently called
632 for discussions on security, ethical, and governance issues around sea ice
633 thickening and other Arctic ice management techniques.

634 **Amount of attention in scientific journals and public media and currently**
635 **ongoing research programs**

636 **Score:** Medium **Confidence:** High

637 Sea ice thickening has been featured in popular media (See for example the
638 prominent reports of Desch' 2017 plan by McKie, 2025, in The Guardian and by
639 Bukszpan, 2017 in CNBC). There has been limited academic coverage of this idea
640 besides the studies already cited here, although there are government and industry
641 reports on the regular practice of sea ice thickening for the construction of ice roads,
642 airstrips, and drill platforms (C-CORE 2005; Andreeva and Sharapov 2023; Daly et
643 al. 2023)

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Sea ice arches with artificial structures

Sea ice arches are natural structures that form seasonally in narrow Arctic straits — most notably the Nares Strait between Ellesmere Island and Greenland — and act as gatekeepers that block the southward export of thick, multi-year ice. Climate change is destabilizing these arches: their average seasonal duration in the Nares Strait has shortened from 177 to 128 days over the past four decades, and years without arch formation are becoming more frequent, leading to doubled ice export fluxes. The second, more speculative and more intrusive variant to arch reinforcement involves replacing or supplementing natural ice floes with artificial structures — buoyant physical elements anchored or positioned across the strait — designed to mechanically recreate the arch effect even in the absence of sufficient natural sea ice, thereby ensuring year-round limitation of ice export regardless of ambient ice thickness. This approach represents geographically targeted, relatively localised interventions with potentially large Arctic-scale benefits, and a contribution to global albedo. Key uncertainties concern the structural integrity of reinforced arches against the immense momentum and mechanical forces exerted by a drifting ice pack, ecological impacts, governance, the long-term feasibility of maintaining artificial structures in a harsh marine environment, and the serious navigational hazard that such structures would pose should they be designed as free-floating elements from the outset or become detached from their moorings under ice pressure.

Issue being addressed

Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker open water during Arctic summers, further accelerating warming through the ice-albedo feedback. The decrease in albedo of the Arctic Ocean as a consequence of diminishing sea ice has increased global warming in recent decades by about 25% of the warming due to greenhouse gas emissions (Pistone et al. 2014). Including the effect of diminishing terrestrial snow cover increases the contribution of reduced albedo to about 44% of the warming due to fossil fuel emissions (Marcianesi et al. 2021).

A key but often overlooked driver of Arctic sea ice loss is the lateral export of sea ice through narrow Arctic straits. In the Nares Strait alone, the absence of a natural ice arch — which in recent decades has become more frequent as ice thins — allows approximately 100,000 km² of thick, multi-year ice to be flushed southward into Baffin Bay each year (Moore et al. 2021). This exported ice is irretrievably lost to the Arctic system, representing a net drain on the oldest and most climate-relevant ice class. As climate change continues to thin and weaken the natural ice arches that seasonally block these export pathways, their protective function is diminishing, compounding the loss driven by in-situ melting.

690 **Description of the technology/ measure**

691 details are available, but to our best knowledge, that method imply envisions
692 replacing or supplementing natural ice floes in the arch with purpose-built artificial
693 structures — buoyant, mechanically robust elements anchored or positioned across
694 the strait — designed to recreate the load-bearing arch geometry even in the
695 absence of sufficient natural sea ice, thereby providing a year-round barrier to ice
696 export regardless of ambient ice thickness.

697 **Technological readiness**

698 **Score:** Low **Confidence:** High

699 Very limited information is currently available, and at this stage the proposal should
700 be regarded primarily as a conceptual idea rather than an operationally developed
701 intervention

702 **Scalability**

703 **Score:** High **Confidence:** High

704 The sea ice arch approach concentrates the intervention at a small number of
705 geographic choke points where the impact per unit of effort is maximised. The Nares
706 Strait, with a width of only ~35 km, controls the export of approximately 100,000 km²
707 of multi-year ice per year when the arch is absent; reinforcing or recreating an arch
708 at this single location could thus yield an Arctic-scale benefit at a fraction of the
709 infrastructure cost of distributed thickening. This targeted, high-leverage geometry is
710 the primary argument in favour of a high scalability score, albeit contingent on the
711 intervention proving structurally and mechanically feasible.

712 **Timeliness for near-future effects**

713 **Score:** Low **Confidence:** Low

714 Given the early conceptual stage of the approach and the absence of field trials, any
715 climatically relevant benefits are unlikely to materialise in the near future, even
716 though exploratory pilot experiments might be feasible within the next decade

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

718 **Score:** High **Confidence:** High

719 A modeling effort suggested slowing the loss of Arctic sea ice would result in a global
720 forcing of -0.08 W/m² for the period of 2061–2100 (Zampieri and Goessling (2019).
721 Both Zampieri and Goessling (2019) and Pauling and Bitz (2021) point out that, at
722 best, thickening sea ice would likely only delay the eventual disappearance of Arctic
723 summer ice. Such a delay, however, could critically increase the time to reduce
724 greenhouse gas concentrations in the atmosphere. Thus, we assess the potential to
725 make a difference in Northern—including Arctic—environments to be high.

Potential to make a global difference

Score: Low **Confidence:** –

If more Arctic sea ice could actually be preserved, ice thickening would have some effect on the global energy budget. A model study found a global - 0.08 W/m² forcing effect for the period of 2061–2100 (Zampieri and Goessling 2019). Both Zampieri and Goessling (2019) and Pauling and Bitz (2021), however, also find that although certain pumping strategies might lead to better results, they would only delay the eventual disappearance of Arctic summer ice under expected warming scenarios. In Cambridge Bay, artificially thickened sea ice was still 40 cm thick in July when control area ice had melted away (Blanchard-Wrigglesworth et al. 2026). In contrast, ice artificially thickened in Vallunden Lagoon, Svalbard in 2024 did not persist longer than control ice, a result that may have been particular to the conditions in Vallunden Lagoon (Hammer et al. 2026).

Cost - Benefit

Score: Moderate **Confidence:** Low

Very little information is currently available to support robust cost estimates for this approach. Nevertheless, it is reasonable to expect that the design, fabrication, transport, deployment, and maintenance of artificial structures capable of emulating large ice floes in dynamically active straits would be expensive. At the same time, the strong geographical focus on a limited number of strategic choke points, rather than on vast areas of the Arctic Ocean, could partially offset these costs and make the overall cost–benefit profile more favourable than that of interventions that require treating extensive sea-ice surfaces. A further crucial unknown for assessing cost–benefit is whether such structures would be designed to persist in place from one year to the next or to be strictly seasonal. Perennial installations could substantially reduce annualised costs by avoiding repeated fabrication and deployment, but this would come at the price of heightened concerns about ecological impacts and increased hazards for navigation.

Likelihood of environmental risks

Score: Some risk **Confidence:** Low

There is very little information on the design and deployment of artificial floe-like structures intended to promote or buttress sea-ice arches, including key characteristics such as their size, materials, and whether they would be seasonal or perennial installations. Nevertheless, insights from studies of artificial floating islands and modular floating platforms indicate that comparable structures can substantially modify local marine ecosystems by introducing new hard-substrate habitat, altering small-scale hydrodynamics, and attracting fish, invertebrates, and birds, with potentially mixed effects on community composition and trophic interactions (e.g. Tamis et al., 2021; Fonseca et al. 2015; Flikkema et al., 2020). By analogy, artificial ice-floe-like structures used to support sea-ice arches in high-latitude straits are

therefore likely to entail a non-negligible likelihood of environmental risks, even though the magnitude and spatial extent of such impacts remain highly uncertain owing to the absence of targeted empirical studies in polar, ice-associated settings (Tamis et al. 2021; Fonseca et al. 2015). It is worth noting that, in temperate coastal marine environments, AFIs have in some cases been shown to generate positive ecological effects, including the formation of biofouling communities that increase local productivity and attract higher trophic level species such as fish (Ware & Callaway 2019; Tamis et al. 2021), as well as providing habitat for juvenile fish, invertebrates, and seabirds (Ware & Callaway 2019). However, these documented benefits arise in systems that are already substantially modified by human activities, whereas Arctic marine environments remain comparatively pristine and are likely to be more sensitive to anthropogenic perturbations. To the best of our knowledge, no peer-reviewed studies have specifically examined the ecological effects of artificial floating structures in Arctic marine environments, and given the fundamental differences in species communities, ice dynamics, and physical conditions between temperate coastal settings and ice-covered Arctic straits, any extrapolation of these positive effects to floe-like structures deployed to support sea-ice arches must therefore be treated with caution.

Effects on local/ indigenous communities

Score: Unknown

Confidence: High

The approach is only at the conceptual stage, too early to assess the impact on local/Indigeneous communities. Information on any co-production with local/indigenous communities is not available.

Ease of reversibility

Score: Medium

Confidence: Medium

The intervention appears in principle reversible, as the artificial floe-like structures could be physically removed from the deployment site, either at the end of the season or upon termination of the programme. However, reversibility may be complicated in practice by the fact that the structures could become temporarily embedded within the sea-ice cover during the winter growth season, making their retrieval difficult, potentially damaging, or dependent on seasonal ice melt. Any ecological changes induced by the presence of the structures — such as shifts in local community composition or the establishment of biofouling organisms — would also take time to reverse following removal, adding a degree of ecological inertia to the physical reversibility of the intervention. Overall, reversibility is considered feasible but operationally non-trivial, or logistically demanding, and is therefore rated as medium

803 **Risk of termination shock**

804 **Score:** Some risk **Confidence:** Medium

805 The risk of termination shock associated with this intervention is considered
806 moderate and geographically limited. Unlike solar radiation management
807 approaches, where abrupt termination can trigger rapid global warming, the
808 cessation of artificial arch support structures would primarily affect the export flux of
809 thick multi-year ice through the targeted straits. For seasonal deployments, removal
810 of the structures at the end of each season implies that no long-term commitment is
811 created and the system returns to its natural state without abrupt transition.
812 However, if perennial structures were to maintain arches that would not otherwise
813 form naturally, their sudden removal could lead to a rapid resumption of ice export
814 and an accelerated loss of multi-year ice in the upstream basin, representing a
815 regional, if not global, termination shock. The risk is therefore rated as some risk,
816 reflecting the distinction between seasonal and perennial deployment scenarios and
817 the regionally confined nature of the intervention.

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

819 **Score:** Challenging **Confidence:** Low

820 The suitability of this intervention within current legal and governance frameworks is
821 challenging. A critical issue concerns the mode of deployment and, in particular,
822 whether the structures can be reliably maintained in a fixed position. Holding artificial
823 floe-like structures stationary in an active sea-ice environment would be extremely
824 difficult, given the immense forces and momentum energy exerted by a drifting ice
825 pack, which could displace, damage, or destroy any anchoring system. Should the
826 structures be unable to remain in place and drift freely, they would pose a serious
827 navigational hazard to vessels operating in the strait. Under international maritime
828 law — in particular the International Convention for the Safety of Life at Sea
829 (SOLAS) (IMO 1974) and the Convention on the International Regulations for
830 Preventing Collisions at Sea (COLREGS) — unattended drifting structures in
831 navigable waters are not permitted, as they constitute an unacceptable risk to
832 shipping safety (IMO 1972, 1974). Any deployment would therefore require either
833 robust anchoring capable of withstanding sea-ice forces, continuous monitoring and
834 attendance, or systematic seasonal recovery prior to the opening of navigation
835 routes. Beyond these navigational and safety constraints, the deployment of such
836 structures in Arctic straits such as Nares Strait, which border national jurisdictions
837 and are subject to competing sovereignty and navigation rights claims, would raise
838 additional governance challenges that currently lack a dedicated international
839 regulatory framework.

840 **Amount of attention in scientific journals and public media and currently**
841 **ongoing research programs**

842 **Score:** Medium

Confidence: High

843 There has been limited media coverage, and it was difficult to find information online.

844 For the time being the method has only been presented at conferences.

845

Draft for Review

Draft for Review

Sea ice albedo modification

Overall assessment:

According to the Arctic Ice Project's white paper (Zornetzer et al. 2021), the HGM approach is currently estimated to be at Technology Readiness Level (TRL) 3, indicating that the main features have undergone successful proof-of-concept testing, including initial demonstrations of the effectiveness, practicality, and safety of the concept. In a recent paper, Farkas et al. (2023) report significant differences in the properties of different HGM types and show that some materials may leach into seawater over time. Consequently, further research is required to better understand the environmental impacts, lifetime, and behaviour of HGM, particularly under harsh Arctic weather conditions. The reflectiveness of HGM and their radiative effect are debated (Warren and Webster 2022; Strawa et al. 2025; Warren and Webster 2025). This is critical because, depending on their reflectiveness, dispersing HGM could instead reduce surface albedo. Warren and Webster (2022) note that offshore winds could significantly reduce the effectiveness of this technique. Siegert et al. (2025) raised legal concerns about the wind dispersion of HGM, and pointed out that local communities must be consulted before large-scale deployment. Impacts of spreading of HGM over land has not been addressed.

Overall, dispersing significant quantities of materials across vast expanses of ocean surface in one of the most pristine environments on the planet appears to be a fundamentally anachronistic approach, at least without a comprehensive assessment of the ecological impacts of HGM dispersal, both in ocean water column, seafloor, but also land as wind will likely disperse HGM on long distances. Recent laboratory experiments examining the effects of HGM on marine organisms have demonstrated measurable impact and call for further comprehensive studies before any large scale deployment.

The albedo-enhancement concept promoted by Arctic Ice Project (ex-Ice911) has now been discontinued, following the organization's 2025 decision to end research (<https://www.arcticiceproject.org/a-final-chapter/>) and wind down based on ecological and social concerns that have been raised by leading polar scientists and expert groups (e.g. Miller et al. 2020; Siegert et al. 2025; Warren and Webster 2025).

Issue being addressed

Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.

Description of the technology/ measure

Apart from thickening sea ice by directly adding mass to it (see sea ice thickening), it has been suggested that the ice could also be protected by increasing its albedo and

thereby reducing the amount of absorbed energy (Field *et al.* 2018). For a decade, the non-profit organization Arctic Ice Project studied the feasibility of increasing albedo by spreading hollow glass microspheres (HGM) on top of sea ice (<https://www.arcticiceproject.org/the-project/>). Citing concerns about toxicity of the beads, funding constraints, and broad resistance to geoengineering, the Arctic Ice Project announced that it was concluding their research and ceasing operations.

Technological readiness

Score: Low

Confidence: Medium

HGM are already used for different purposes, and these kinds of microspheres made out of silica are commercially produced and available (Field *et al.* 2018). The global demand of HGM is, however, rather limited and production would have to be significantly increased if substantial parts of Arctic sea ice were to be covered with them. Current research is looking at whether these HGM could effectively preserve Arctic sea ice without causing unwanted side effects.

Through the non-profit organization Ice911, Leslie Field, who first suggested using HGM, started conducting several field trials in North America, mainly on freshwater ponds. Field, however, recently left the organization and is now exploring the possibility to use HGM on mountain glaciers (see glacial albedo enhancement). Ice911 has since been renamed Arctic Ice Project. The organization works together with companies and institutions like Climformatics and Harvey Mudd College for their modeling and simulations, and are currently in a 'multi-year, multi-million dollar' collaboration with Norwegian organization SINTEF aimed at 'materials testing, safety, performance testing and methods for deployment' (<https://www.arcticiceproject.org/the-project/>). Arctic Ice Project's white paper (Zornetzer *et al.* 2021) estimates their HGM idea to be at Technology Readiness Level 3, stating 'that the main features have undergone successful proofs of concept, including successful initial demonstrations of the effectiveness, practicality, and safety of the approach. In a recent pre-peer review manuscript, Farkas *et al.* (2023) describe that their experiment found significant differences in properties between different kinds of HGM, and established that some materials leached into seawater overtime. Research is, therefore, still needed about HGM's environmental impacts, lifetime, and behaviour, especially under harsh weather conditions. Warren and Webster (2022) commented on the paper of Field *et al.* (2018), and claimed that HGM would be detrimental to overall Arctic sea ice albedo and whether this sets back its development. In reaction, Strawa *et al.* (2025) substantially revised the optical properties of K1 hollow glass microspheres, showing that their absorptance is only a few percent and that the break-even albedo is close to 0.8 rather than ≈ 0.61 as assumed by Webster and Warren (2022). With these updated values, the same radiative framework no longer supports the conclusion that HGM generally darken Arctic surfaces, since a wider range of ice and melt-pond albedos falls into the "brightening" regime. However, when these model calculations are compared to field experiments, Warren (2025) shows that the revised model still overestimates the

observed albedo increase, and this discrepancy is largest when the more favorable optical constants from Strawa et al. (2025) are used.

Another concern raised by Webster and Warren (2022), and not addressed by Strawa et al. (2025) is that wind, waves, and surface roughness will rapidly redistribute hollow glass microspheres, challenging the assumption of a persistent, spatially uniform brightening layer over Arctic sea ice. In practice, wind-driven drift and wave action are expected to concentrate HGM into bands, leads, or pond margins, and to mix a significant fraction into the upper ocean once the ice and ponds begin to melt, thereby reducing the areally averaged albedo gain relative to what is inferred from small, sheltered test sites.

Scalability

Score: Medium

Confidence: High

Field *et al.* (2018) wrote that current supplies of HGM are insufficient for a large-scale deployment, but that production could likely rapidly be enhanced if needed, thereby also driving down costs. The idea would be to distribute the material at strategic locations in the Arctic, like the Beaufort Gyre, where they would incur greatest effect. However, since it is unclear if the material will be effective outside an experimental setting, and would not be blown away as suggested by Warren and Webster (2022), uncertainties remain about possible scalability.

Timeliness for near-future effects

Score: Medium

Confidence: High

Publications related to the Arctic Ice Project are more optimistic about the potential timeliness of this scheme (see for example Zornetzer et al. 2021). However, even though HGM already exists, due to the many technical issues and large parts of the ice already gone, the potential window to implement such an intervention seems increasingly limited.

Potential to make a difference in Northern + Arctic

Score: Medium

Confidence: Medium

A report by Arctic Ice Project states that their experiment showed that a treatment with HGM increased an area's average albedo from 0.17 to 0.36, while the ice thickness reduced from 20 cm to 10 cm in the melt period and that the observed '30% reduction in radiative energy into the pond from surface modification with HGMS cause[d] a proportional 30% reduction in ice melt rate' (Johnson *et al.* 2022). Zornetzer *et al.* (2021) furthermore claim that modeling has shown 'that yearly [springtime] application of the material on the Arctic sea ice over the period 2000–2040 would cause/ have caused ice volume to increase 0.5 percent to 1 percent per year, with increased ice thickness of 20 cm to 1 m', and that this would lead to Arctic temperature decreases of up to 1.5°C.

Warren and Webster (2022), however, strongly question these findings and argue that Arctic Ice Project's studies did not take ice and snow specificities and weather into consideration, and that this technology would in fact not slow, but rather increase the overall rate of melting. However, timing is critical; completely non-absorbing microspheres might increase ice albedo. Warren and Webster write in an AGU joint release (2022) that this "might still not solve the problem because of a simple reason: quantity. About 360 million tons would be needed for a once-annual application to prevent ice melt and cool the climate. And that's assuming the non-absorbing microspheres could be manufactured and dispersed without contamination or other unintended effects." Apart from this production and distribution problem, the potential to form a functional layer of reflective particles is also questioned because winds would likely blow them away or clump the particles together, a phenomenon the authors say is already observed in the very small experimental ponds.

Model studies suggest that even though HGM might lead to some ice preservation (Cvijanovic et al. 2015), the ice will probably completely disappear anyway if current warming trends continue (Zampieri and Goessling 2019). Moreover, Zhao et al. (2021) found that Marine Cloud Brightening could have a 40% greater forcing efficacy than surface albedo modifications like HGM application along with the extra benefit of also reducing shortwave heating of the lower atmosphere.

Potential to make a global difference

Score: Medium

Confidence: Medium

If significant amounts of Arctic sea ice could be preserved, this could have a major effect on the global energy budget. However, in absolute terms, the global radiative forcing effects of HGM sea ice modification will likely remain limited (Cvijanovic et al. 2015).

Cost - Benefit

Score: Moderate

Confidence: Medium

The HGMs are intended to be applied at strategic locations where they would have maximum effect. The cost of such limited application would still remain high. Field et al. (2018) estimate that production costs for a treatment of 25,000 km² with microspheres would be around \$300,000,000 at current prices, with some 10 million UDS added for transportation. It should be noted that these costs would likely decline if production were to be scaled. Moreover, Hao et al. (2023) estimate that the melting of the sea ice would in any case costs the world an average of 6.7–13.3 trillion USD annually over the period 2020 to 2100, when the costs of the forcing effects of the ice are calculated in terms of equivalent costs of the forcing that is the result of GHG emissions. Siegert et al. (2025) argue that the economic viability of large-scale glass-bead deployment is highly questionable. When the costs of materials, manufacturing, logistics, and the extensive research and regulatory processes required for authorization are taken into account, they conclude that this

option is likely to be economically unattractive compared with straightforward greenhouse-gas mitigation and adaptation measures

Likelihood of environmental risks

Score: Some risk **Confidence:** Medium

The Arctic Ice Project claims their material is non-toxic (see for example Zornetzer et al. 2021). This is important, as Farkas et al. (2023) found that some HGM variants they tested in their experiment leached into seawater over time. Miller et al. (2020) still warn about the project's potential effects on biochemistry because, like sea ice thickening, this measure would likely increase aerosol levels in the atmosphere leading to changes in air temperature due to cloud formation and could influence bioproductivity in the ocean by limiting light availability. The use of silicon-based spheres could moreover have a fertilization effect and thereby impact the blooming of algae; beads were shown to be eaten by zooplankton and to block the gut. Small, sinking and biofouled HGMs were ingested most efficiently, but toxicity appears physical rather than chemical, with HGM behaving as inert, non-nutritive particles that can impair condition and survival when exposure is sustained or extreme (Farkas et al. 2025).

In the Arctic, seven species of pinnipeds depend on the surface of sea ice as habitat for resting, molting, and rearing young. Polar bears are specialized to prey on those seals and walruses on the ice (Fay 1974; Kelly 2001, 2022; Hezel et al. 2012). We are not aware of any studies of how ice-associated mammals would cope with the addition of foreign materials to their sea ice habitat.

Effects on local/ indigenous communities

Score: Negative **Confidence:** Medium

The Arctic Ice Project emphasizes that it wants to collaborate with indigenous groups. On their website they write they want to 'do no harm' to the 'environment, nor the tribes, communities, and animals that call the Arctic home in the attempts to restore ice' (www.arcticiceproject.org/the-project/).

However, in early 2022 the organization faced criticism after indigenous-led protests at a fundraising event (see Elliott 2023), which was followed by a letter of protest that called for a termination of all the organization's intended activities in the Arctic (<https://docs.google.com/document/d/1G5b-MSKyV5cl96lyBV140jhyfE-SaPTEt85aVZC5TjM/edit>).

Indigenous Arctic communities, whose rights, livelihoods and cultural relationships with sea ice would be directly affected, implying that any serious consideration of glass-bead deployment would require their meaningful involvement and explicit support from the outset, in particular in light of wind redistribution of HGM over land.

1045 **Ease of reversibility**

1046 **Score:** Medium **Confidence:** High

1047 The distribution of material could be halted at any point. Depending on the reason for
1048 reversing, the material would potentially have to be removed at some cost.

1049 **Risk of termination shock**

1050 **Score:** Low risk **Confidence:** High

1051 The ice would probably melt away quickly without continuous treatment. The time to
1052 melt depends on accumulated thickness, but at termination the glass microspheres
1053 are left in the environment.

1054 **Suitability within current legal/ governance structures**

1055 **Score:** Challenging **Confidence:** High

1056 Although it is not clear how the deployment of HGM would be governed on the High
1057 Seas, the five Arctic coastal states would likely be able to distribute them within their
1058 Exclusive Economic Zone if they wanted to (Moore et al. 2020), albeit with likely
1059 many objections from various local interests. The project would face difficulties in
1060 terms of governance because distribution areas would be both on states' territorial
1061 and international waters, and would therefore be liable to both national and
1062 international legislation. Argüello and Johansson (2022), therefore, call for active
1063 research to see how Arctic ice management techniques might be governed. Siegert
1064 et al. (2025) build on Webster and Warren's (2022) argument that hollow glass
1065 microspheres would be rapidly redistributed by winds and waves, challenging the
1066 assumption of a persistent, spatially uniform brightening layer over Arctic sea ice.
1067 They further stress that glass-bead deployment raises major governance issues,
1068 because ocean currents and surface winds would carry beads across jurisdictions,
1069 effectively exporting an environmental disturbance without consent; in their view, the
1070 absence of specific international rules to manage such transboundary impacts
1071 currently constitutes a significant barrier to large-scale deployment.

1072 **Amount of attention in scientific journals and public media and currently**
1073 **ongoing research programs**

1074 **Score:** High **Confidence:** High

1075 The albedo-enhancement concept promoted by Arctic Ice Project (ex-Ice911) has
1076 now been discontinued, following the organization's 2025 decision to end research
1077 (<https://www.arcticiceproject.org/a-final-chapter/>)

1078 and wind down over ecological and social concerns that have been raised by leading
1079 polar scientists and expert groups (e.g. Miller et al. 2020, Siegert et al. 2025; Warren
1080 and Webster 2025).

1081

1082 **Sea ice breakup in winter**

1083 Overall assessment: The original idea is to increase winter heat loss from the Arctic
1084 Ocean by decreasing the sea ice area. The methods are a) icebreaking, and b)
1085 weakening the ocean stratification. a) would produce more ice due to opening and
1086 ridging, more multiyear ice as well, and the global impact would be cooling; b) works
1087 but the decreased ice extent would be disastrous to the arctic ecosystem and arctic
1088 indigenous peoples.

1089 **Issue being addressed**

1090 Sea ice is a thin layer between the atmosphere and the ocean with a large impact on
1091 the transfer of heat, momentum, and matter between these media. In winter its very
1092 low thermal conductivity, as compared with the turbulent conductivities of air and
1093 seawater, reduces the air–sea heat transfer and, consequently, radiative and
1094 turbulent heat losses from the ocean, thereby reducing the potential dissipation of
1095 heat into space.

1096 **Description of the technology/ measure**

1097 There have been occasional undeveloped references to the idea to break up sea ice
1098 in winter with icebreakers to increase the amount of outgoing radiation (see, for
1099 example, Roewe & Kallio 2009). Breakage by icebreaker would also lead to pile-up
1100 of ice blocks that would be an additional ice generating mechanism.

1101 Apart from such isolated references, Hunt et al. (2020) provide some back-of-the-
1102 envelope calculations on the potential radiative effects of sea ice breakup, and
1103 suggest several methods by which to do this. Many of the authors' ideas about Arctic
1104 sea ice removal are reminiscent of earlier plans by Russian and Soviet scientists and
1105 engineers to melt the Arctic in order to “ameliorate” the northern climates. Hunt *et al.*
1106 (2020) even directly cite some of these earlier ideas to legitimize their plan. They
1107 ultimately consider the following options: (1) Pumping freshwater down to make it
1108 less likely for ice to form, (2) Reducing the melting of the Greenland ice sheet
1109 thereby limiting freshwater inflow, and (3) Deviating the rivers in the Northern
1110 Regions to reduce freshwater inflow into the Arctic. These methods (1)-(3) would
1111 weaken the stability of the stratification of the Arctic Ocean that deepens the cold
1112 upper ocean layer, and the incoming deep oceanic heat flux to the surface would
1113 then decrease ice growth in winter. Arctic sea ice cover would function more toward
1114 the sea ice cover in the Southern Ocean with lower extent and thickness. A much
1115 more open Arctic Ocean would have more terrestrial radiation and turbulent losses in
1116 winter decreasing the global heat storage. How much heat would be lost to space
1117 depends on the resulting changes in atmospheric temperature and humidity. Finally,
1118 note that changing of the stratification by itself gives the desired decreased ice
1119 volume and heat loss, and the use of icebreakers as suggested is not necessary.

1120 As said, use of the icebreakers could have an opposite effect. Considering only the
1121 opening of sea ice cover by icebreakers, intensive growth of new ice would result

1122 since the upper ocean layer is at the freezing point temperature. Breaking sea ice
1123 using icebreakers produces open spots where ice growth can be fast. The growth
1124 rate of bare ice is inversely proportional to ice thickness. Thus, thin ice grows 5–10
1125 times faster than thick ice. The broken ice floes removed from the open water spots
1126 are pushed above and below the existing ice and increase the thickness there. This
1127 extra ice will mean a larger volume of sea ice survival over summer with larger
1128 albedo effect, and there will be more multi-year sea ice in the following winter.
1129 Breaking sea ice would increase radiative (and turbulent) heat losses from the ocean
1130 to the atmosphere in winter. In all, the plan contains two different methods –
1131 stratification change and icebreakers – with remarkably different outcomes for sea
1132 ice extent and thickness in the Arctic.

1133 **Technological readiness**

1134 **Score:** Low **Confidence:** Low

1135 Apart from the highly questionable assumption that it would be beneficial to get rid of
1136 Arctic ice, and setting aside the question whether this would require enormous
1137 engineering projects in face of already rapidly declining ice levels, the plans
1138 suggested by Hunt *et al.* (2020) belong to the realm of speculative mega-engineering
1139 projects that are nowhere close to being operationalised.

1140 There are two opposing results. One is that ice breaking would produce more ice
1141 due to accumulation of ice blocks (ridges) while increasing the heat loss? This would
1142 increase summer albedo and lead to more multi-year ice. The other is that cutting
1143 freshwater flux would decrease ice growth. The freshwater from rivers is the main
1144 source; Greenland meltwater flows mostly south, and deepening the upper layer by
1145 pumping is too demanding. Finally, the goal of smaller ice volume contradicts the
1146 goal of conserving sea ice.

1147 **Scalability**

1148 **Score:** Low **Confidence:** High

1149 Breaking the ice at large scale will be logistically very demanding. Pumping
1150 freshwater down in significant amounts in the Beaufort sea, as suggested by Hunt *et al.* 2020, if feasible, will have a large impact on a large scale, so scalability is less of
1151 an issue than feasibility for that approach.
1152

1153 Deriving rivers will also have a large impact. Without prejudging the feasibility of
1154 diverting massive volumes of freshwater from rivers - Arctic ocean receives up to
1155 about 10 % of global riverine freshwater inputs - the main freshwater sources are
1156 geographically concentrated in four major rivers (Yenisey, Lena, Ob' and
1157 Mackenzie), so only a limited number of installations would be required, with the
1158 largest potential impacts likely associated with the Russian rivers that affect a large
1159 area. So scalability is less of an issue than feasibility for that approach.

1160 **Timeliness for near-future effects**

1161 **Score:** Low **Confidence:** High

1162 The engineering projects to cut freshwater flux would take a very long time to
1163 develop and implement, if one is at all feasible. Icebreaking would be feasible over a
1164 short time.

1165 **Potential to make a difference in Northern + Arctic**

1166 **Score:** High **Confidence:** High

1167 There are no clear technological pathways to cut freshwater flux, and it is highly
1168 questionable if it would be desirable to remove Arctic sea ice. This effort would
1169 clearly have a huge impact on the climate and ecology in the Arctic subarctic
1170 regions. Apart from the removal of the ice itself, the increased release of heat and
1171 moisture from the Arctic Ocean would warm surrounding air and have a large
1172 warming and moisturizing effect on the Eurasian and North American continents

1173 **Potential to make a global difference**

1174 **Score:** High **Confidence:** High

1175 Hunt *et al.* (2020) do not attempt to provide any definitive calculations on this.
1176 Removing sea ice in winter would increase outgoing radiation and turbulent transfer
1177 of heat and moisture that would influence the weather and climate in the Northern
1178 Hemisphere. The resulting lack of sea ice in spring would undoubtedly lower the
1179 Earth's albedo and thereby increase ocean energy absorption.

1180 **Cost - Benefit**

1181 **Score:** Prohibitive **Confidence:** High

1182 Hunt *et al.* (2020) admit that the costs for such projects would be prohibitively high.

1183 **Likelihood of environmental risks**

1184 **Score:** High risk **Confidence:** High

1185 Apart from side effects of the chosen method to remove the ice, the destruction of
1186 Arctic ice would severely endanger local ecosystems. The warming in the Arctic as a
1187 result of increased outgoing radiation and turbulent losses would likely be equally
1188 disastrous for the region.

1189 **Effects on local/ indigenous communities**

1190 **Score:** Negative **Confidence:** High

1191 Hunt *et al.* (2020) seemingly uncritically copy the ideas of Soviet scientists about the
1192 amelioration of the North and assume that a warming Arctic would be desirable. But
1193 the destruction of Arctic ice and further warming of the region would be disastrous for
1194 already severely endangered local livelihoods.

1195 Surface travel on sea ice is vital to Indigenous harvests of whales, walruses, seals,
1196 sea birds, and fish across much of the Arctic. In the North American Arctic,
1197 Indigenous communities express considerable alarm over ice breaking in the areas
1198 they harvest.

1199 **Ease of reversibility**

1200 **Score:** Hard **Confidence:** Low

1201 Many of the suggested means by which the ice would be removed would be near-
1202 permanent constructions, and there are many doubts if Arctic winter sea ice could
1203 regrow if removed (see for example the discussion of Arctic winter sea ice as a
1204 tipping point in Armstrong McKay 2022). The stratification could return in the time
1205 scale of decades if the freshwater flux would be returned.

1206 **Risk of Termination shock**

1207 **Score:** Low risk **Confidence:** low

1208 If re-stratification is possible, timescale is decades and impacts unclear.

1209 **Suitability within current legal/ governance structures**

1210 **Score:** Challenging **Confidence:** low

1211 Given the huge objections against it, it is highly unlikely that the removal of Arctic
1212 sea ice and the technologies required to do so could become part of international
1213 legal and governance structures. The sea ice within the Exclusive Economic Zone of
1214 individual countries may however be modified under domestic laws, e.g., by the river
1215 freshwater outflows.

1216 **Amount of attention in scientific journals and public media and currently**
1217 **ongoing research programs**

1218 **Score:** Low **Confidence:** Low

1219 Apart from Hunt *et al.* (2020), there are several estimates in the past that an open
1220 Arctic Ocean would be a stable state. However, this remains a very niche idea that is
1221 not given much credible attention with the exception of de Richter *et al.* (2019) that
1222 mention it. Turning of Siberian rivers to south to help central Asian water supply was
1223 discussed in Soviet papers 50 years ago.

1224

1225

1226 **Pykrete usage**

1227 Overall assessment:

1228 The proposed technique aims to reinforce sea ice by incorporating sawdust or wood
1229 pulp into the ice matrix, thereby increasing its mechanical strength and fracture
1230 toughness while simultaneously reducing its thermal conductivity and slowing its melt
1231 rate. This composite material, known as pykrete, was originally developed during the
1232 Second World War and has since been suggested as a potential means of
1233 reinforcing natural sea ice in the Arctic to slow its seasonal decay and lateral export.
1234 Pykrete slows melting mainly because of its low thermal conductivity and mechanical
1235 stability, but this has only been demonstrated in small-scale lab or outdoor tests
1236 under cold, shaded or weak-sun conditions; the albedo penalty becomes important
1237 under strong solar radiation (Atul *et al.* 2019). This calls for verifying that the adverse
1238 impact of the darkening of the ice in open ocean in summer, with 24 daylight
1239 insulation does not outweigh the reduced thermal expertise. This approach entails
1240 dispersing wood into the open ocean, thereby increasing the organic matter load in
1241 surface waters. This is likely to reduce light transmittance, reduce primary
1242 production, and stimulate heterotrophic respiration. A fraction of the added organic
1243 carbon will be remineralised and released as CO₂ to the atmosphere, and this CO₂
1244 flux should be quantified and incorporated into any cost–benefit assessment of the
1245 method.

1246 **Issue being addressed**

1247 Arctic sea ice extent has rapidly decreased over the last few decades, with most
1248 multi-year ice disappearing altogether. This has already had major effects on local
1249 communities and ecosystems. The disappearance of the relatively reflective sea ice
1250 also leads to a dramatic decrease of albedo in the Arctic and subsequent high
1251 energy uptake by the darker water during the Arctic summers.

1252 **Description of the technology/ measure**

1253 Pykrete is a 6:1 mix of ice and sawdust that has the property of melting slower than
1254 regular ice by lowering thermal conductivity that prevent thermodynamical melting,
1255 and high fracture toughness that slows down sea ice extent reduction by advecting
1256 melting. Several references have been made online to the use of pykrete as an
1257 artificial barrier, as artificial sea ice, or as blockers of moulins.

1258 Pure snow and fresh ice have high albedo (often 0.6–0.9; Abhishek and Zope,
1259 2019), reflecting most shortwave radiation; lowering albedo means more absorbed
1260 solar energy and faster melt for a given conductive/convective environment. Adding
1261 wood fibers darkens the surface relative to clean ice, similar in principle to black
1262 carbon contamination, which is known to enhance absorption and accelerate melt on
1263 snow and ice. Many engineering tests were carried out near 0–32 °C (laboratory or
1264 temperate-outdoor conditions), measuring time to melt of equal-size ice and pykrete
1265 blocks at a fixed air temperature of about 32 °C (≈0 °C) and low wind, often indoors

1266 or in shade. Pykrete appears to slow melting and significantly increase mechanical
1267 strength.

1268 **Technological readiness**

1269 **Score:** Medium **Confidence:** Medium

1270 Pykrete was designed in the twentieth century. and was named after its inventor
1271 Geoffrey Pyke. During the Second World War, it was suggested that an aircraft
1272 carrier could be built from it. However, there have been no serious studies into its
1273 feasibility for any of the suggested purposes. Whether pykrete could withstand the
1274 mechanical stresses, thermal conditions, and dynamic forces encountered in an
1275 open-ocean or sea-ice environment remains an open question that has never been
1276 formally addressed. The only large-scale prototype ever constructed was a model
1277 approximately 18 m in length and weighing around 1,000 tonnes, built on Patricia
1278 Lake in the Canadian Rockies under freshwater and controlled lacustrine conditions
1279 — not in open-ocean settings. The project was ultimately abandoned before any sea
1280 trials could be conducted. More recently, small pykrete boats were built and tested in
1281 calm water as part of television science programmes, including MythBusters
1282 ([Episode 115: Alaska Special 2, 2009](#)) and the [BBC series Bang Goes the Theory](#)
1283 ([Series 3, Episode 6, 2010](#)), but with mixed results: significant leaks appeared
1284 rapidly and the structures degraded within approximately 30 minutes. To the best of
1285 our knowledge, pykrete has therefore never been tested as a floating structure in
1286 open-ocean or sea-ice conditions. Note that this has been seriously proposed for the
1287 construction of offshore oil storage facilities with the advantage that the platform
1288 melts away after use.

1289 **Scalability**

1290 **Score:** Low **Confidence:** Medium

1291 Requires much sawdust, therefore works on a local scale.

1292 **Timeliness for near-future effects**

1293 **Score:** Medium **Confidence:** Medium

1294 Given the very early conceptual stage of this approach and the absence of any
1295 dedicated field studies or engineering assessments in open-ocean or sea-ice
1296 conditions, near-future effects appear unlikely within the next one decade. Resolving
1297 the key uncertainties identified — including the albedo penalty under Arctic summer
1298 radiation, the ecological consequences of wood dispersal in marine surface waters,
1299 and the structural performance of pykrete under dynamic sea-ice conditions — would
1300 require sustained research and development efforts before any deployment at
1301 operationally meaningful scales could be considered. The approach is therefore
1302 rated as medium in terms of timeliness, reflecting the possibility of exploratory pilot
1303 experiments within the next decade, while acknowledging that climatically significant
1304 effects remain distant.

1305 **Potential to make a difference in Northern + Arctic**

1306 **Score:** Low **Confidence:** High

1307 The potential of pykrete to make a meaningful difference in the Northern and Arctic
1308 regions is assessed as low. The approach is fundamentally limited in scalability by
1309 the large quantities of sawdust or wood pulp required, which constrain its application
1310 to local scales rather than basin-wide interventions.

1311 **Potential to make a global difference**

1312 **Score:** Low **Confidence:** High

1313 Given the inherent scalability constraints of the approach — primarily the large
1314 volumes of sawdust required and the logistical challenges of distributing and
1315 incorporating wood pulp into sea ice at basin-wide scales — the potential of pykrete
1316 to contribute to a measurable global climate difference is assessed as low. Even
1317 under optimistic assumptions regarding deployment, the geographic confinement of
1318 any realistic application to small, locally treated areas means that the overall impact
1319 on global mean temperature, sea-level rise, or large-scale ocean circulation would
1320 be negligible.

1321 **Cost - Benefit**

1322 **Score:** Cost-effective **Confidence:** Medium

1323 The raw material cost of pykrete — primarily sawdust or wood pulp, a widely
1324 available industrial by-product — is low compared to most other proposed Arctic sea
1325 ice intervention techniques, which typically require expensive engineered equipment
1326 such as pumping systems, reflective materials, or large-scale marine infrastructure.
1327 In this respect, the approach may be considered relatively cost-effective at small
1328 scales. However, the method of dispersal over sea ice surfaces has not been
1329 defined at this stage, and any deployment over large Arctic ice areas would
1330 inevitably be logistically demanding, requiring substantial vessel or aerial operations
1331 in a remote and harsh environment. The overall cost-benefit assessment therefore
1332 depends critically on the dispersal method ultimately adopted and the spatial scale of
1333 the intervention, both of which remain undefined. Until these parameters are
1334 established, the favourable raw material cost must be weighed against the potentially
1335 high operational and logistical costs of large-scale deployment.

1336 **Likelihood of environmental risks**

1337 **Score:** Some risk **Confidence:** High

1338 The incorporation of wood pulp into the ice matrix is likely to reduce light
1339 transmittance through the ice, thereby hampering primary production both within the
1340 ice and in the underlying water column. Furthermore, as the pykrete-treated ice
1341 melts, the released wood particles and associated dissolved organic matter would
1342 increase the turbidity of the water column, further attenuating light availability for
1343 phytoplankton and under-ice algae during and after the melt season. Additionally, the

1344 dispersal of wood-derived organic matter into surface waters is expected to stimulate
1345 heterotrophic respiration.

1346 **Effects on local/ indigenous communities**

1347 **Score:** Neutral **Confidence:** Low

1348 Little information is available to assess the impacts of pykrete deployment on local
1349 and indigenous communities. Reinforcing sea ice strength could support ice roads
1350 and facilitate ice-based transportation and hunting. But, the potential environmental
1351 risk, including reduced primary production, can have adverse effects on food supply
1352 for local communities

1353 **Ease of reversibility**

1354 **Score:** Medium **Confidence:** Medium

1355 The intervention is physically reversible with minimal effort: ceasing wood pulp
1356 incorporation would be sufficient, with sea ice returning to its normal composition
1357 over subsequent freeze-melt cycles. Ecological reversibility is, however, more
1358 uncertain, as the effects of wood-derived organic matter on light availability, primary
1359 production, and food web structure may persist for multiple seasons following
1360 treatment cessation, with recovery timescales largely determined by the rate of
1361 sawdust degradation in cold Arctic waters.

1362 **Risk of Termination shock**

1363 **Score:** Low risk **Confidence:** High

1364 Ceasing the intervention would allow the sea ice system to return rapidly to its
1365 baseline state without abrupt climatic consequences. Any residual post-cessation
1366 effects are primarily ecological — linked to the persistence of wood-derived organic
1367 matter in the water column — and are localised and unlikely to trigger irreversible
1368 system-level responses

1369 **Suitability within current legal/ governance structures**

1370 **Score:** Challenging **Confidence:** Medium

1371 Although wood pulp is a natural, non-toxic material, its deliberate large-scale
1372 dispersal into Arctic marine waters would likely fall under the scope of the London
1373 Protocol, which regulates the dumping of matter at sea, and would require
1374 environmental impact assessments under the Convention on Biological Diversity and
1375 Arctic Council frameworks. The absence of a dedicated regulatory framework for sea
1376 ice interventions adds further governance complexity, justifying a challenging rating.

1377 **Amount of attention in scientific journals and public media and currently**
1378 **ongoing research programs**

1379 **Score:** Low **Confidence:** High

1380 There have been isolated online references on the use of pykrete. It has, for
1381 example, been featured on the online blog by Joseph Cannon on his blog
1382 CANNONFIRE [https://cannonfire.blogspot.com/2009/10/global-warming-cannon-](https://cannonfire.blogspot.com/2009/10/global-warming-cannon-saves-world.html)
1383 [saves-world.html](https://cannonfire.blogspot.com/2009/10/global-warming-cannon-saves-world.html). Cannon reports that a similar idea has also been mentioned in
1384 TED talks.

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1387

Draft for Review

1388 **Wood Ice Seed**

1389 Overall assessment:

1390 The Ice-Wood concept is supported by a preprint (Li et al., in review, 2025) and a
1391 limited number of small-scale laboratory and pond experiments demonstrating that
1392 chemically treated wooden panels can achieve sub-freezing surface temperatures
1393 through passive radiative cooling and trigger ice nucleation under controlled
1394 conditions. While these results are scientifically promising, the approach remains at
1395 a very early stage of development, and no field experiments in open Arctic conditions
1396 have been reported to date.

1397 The question of large-scale deployment is not addressed in the preprint, and any
1398 realistic implementation over extensive Arctic sea-ice or open-water surfaces would
1399 be logistically demanding, requiring substantial maritime assets to distribute, monitor,
1400 and if necessary retrieve the panels across vast and remote areas. The shading
1401 effect of wooden panels on under-ice primary production raises questions on the
1402 ecological impacts.

1403 Furthermore, should Ice-Wood panels be deployed as free-floating structures in
1404 navigable Arctic waters, they would constitute an unacceptable navigational hazard
1405 under international maritime law — in particular the SOLAS Convention and the
1406 COLREGS — which do not permit unattended drifting structures in shipping lanes.
1407 Any deployment in strategically important straits would therefore require either robust
1408 anchoring or continuous monitoring and retrieval, both of which represent unsolved
1409 engineering challenges at the current stage of development.

1410 **Issue being addressed**

1411 Arctic sea ice extent has rapidly decreased over the last few decades, with most
1412 multi-year ice disappearing altogether. This has already had major effects on local
1413 communities and ecosystems. The disappearance of the relatively reflective sea ice
1414 leads to a dramatic decrease of albedo in the Arctic and a subsequent increase in
1415 solar energy uptake by the darker open water during Arctic summers, further
1416 accelerating warming through the ice-albedo feedback. The progressive expansion
1417 of ice-free open water areas during autumn, as temperatures begin to drop below
1418 freezing, represents both the core problem and the primary deployment window
1419 targeted by the Ice-Wood approach: by floating on open water surfaces and
1420 maintaining a sub-freezing surface temperature through passive radiative cooling,
1421 Ice-Wood panels aim to trigger and accelerate the onset of new sea ice formation,
1422 thereby advancing the seasonal freeze-up and extending annual sea ice coverage.

1423 **Description of the technology/ measure**

1424 Li et al. (in review 2025) proposed an approach involving wood-based material - the
1425 ice-wood - Ice-Wood is a solid piece of natural wood that has been chemically and
1426 physically modified through partial delignification (yielding a highly reflective white
1427 surface, albedo = 0.911) and surface carbonization (yielding a high mid-infrared

1428 emittance = 0.941). Floating on the ocean surface, Ice-Wood acts as a passive
1429 radiative cooling platform that reaches sub-freezing temperatures and induces sea
1430 ice formation in its surroundings via radiative cooling and capillary-driven seawater
1431 uptake. Ice-Wood as the potential to generate ice.

1432 This approach entails dispersing wood into the open ocean, thereby increasing the
1433 organic matter load in surface waters. This is likely to reduce light transmittance,
1434 reduce primary production, and stimulate heterotrophic respiration. A fraction of the
1435 added organic carbon will be remineralized and released as CO₂ to the atmosphere,
1436 and this CO₂ flux should be quantified and incorporated into any cost–benefit
1437 assessment of the method.

1438 **Technological readiness**

1439 **Score:** Medium

Confidence: Medium

1440 The proposed Ice-Wood concept is currently at medium technological readiness
1441 level, as it has only been demonstrated at laboratory scale and in limited field trials in
1442 small open ponds. The study establishes key physical principles (high albedo, high
1443 mid-infrared emittance, and capillary transport through the wood microchannel
1444 network) and shows that these properties can trigger earlier ice formation and
1445 enhance ice preservation under controlled conditions. However, the method has not
1446 yet been tested under the full range of Arctic environmental forcings, nor has its
1447 performance been evaluated at spatial and temporal scales relevant for regional
1448 sea-ice management. Critical steps remain before any operational deployment can
1449 be envisaged, including optimization of material durability in marine settings,
1450 assessment of ecological and biogeochemical impacts, development of scalable
1451 manufacturing and deployment logistics, and integration with climate and sea-ice
1452 modelling frameworks to quantify system-level effectiveness and risks. At this stage,
1453 Ice-Wood should therefore be regarded as a promising but still exploratory approach,
1454 requiring substantial further research, pilot-scale demonstrations, and
1455 interdisciplinary assessment before progressing towards higher technological
1456 readiness

1457 **Scalability**

1458 **Score:** Low

Confidence: High

1459 There is currently no detailed description of large-scale deployment pathways for the
1460 Ice-Wood concept in Li et al. in review 2025. The proof-of-concept prototypes
1461 reported so far are small plates with lateral dimensions of only about 10 cm by 10
1462 cm, which are suitable for laboratory and pond-scale experiments but do not directly
1463 translate to operational Arctic applications. The fabrication of larger boards or
1464 modular panels to increase the treated surface area seems possible, yet any realistic
1465 large-scale implementation in coastal or offshore regions would require the
1466 mobilization of substantial maritime assets to distribute and maintain these structures
1467 over extensive sea-ice domains, unless alternative, more autonomous deployment

1468 strategies are developed. At this stage, the study therefore leaves the question of
1469 large-scale deployment essentially open, beyond a qualitative statement that the
1470 concept may inspire future scalable ice-regeneration actions.

1471 **Timeliness for near-future effects**

1472 **Score:** Medium **Confidence:** Medium

1473 Currently limited to laboratory and pond-scale prototypes, the Ice-Wood concept
1474 requires substantial further development before any Arctic deployment becomes
1475 feasible. Near-future pilot experiments at larger scales appear achievable, but
1476 climatically meaningful effects within the next decade are unlikely given the
1477 unresolved engineering and logistical challenges of large-scale deployment.

1478 **Potential to make a difference in Northern + Arctic**

1479 **Score:** Low **Confidence:** Medium

1480 The potential of the Ice-Wood approach to make a meaningful difference at the
1481 Northern and Arctic scale is assessed as low. While the radiative cooling principle
1482 demonstrated at laboratory and pond scale is scientifically sound, the enormous
1483 surface areas that would need to be covered to influence Arctic sea ice extent at a
1484 regional scale represent a formidable logistical challenge that remains unresolved.

1485 **Potential to make a global difference**

1486 **Score:** Low **Confidence:** Medium

1487 Given the insurmountable logistical constraints of deploying Ice-Wood panels at the
1488 scales required to influence Arctic sea ice at a basin-wide level, any contribution to
1489 global climate metrics — such as global mean temperature, planetary albedo, or
1490 sea-level rise — is assessed as negligible. The intervention is inherently local in its
1491 direct physical effect, and even under optimistic scaling assumptions, the treated
1492 surface area would remain a small fraction of the Arctic Ocean. The global climate
1493 impact of the approach is therefore rated as low.

1494 **Cost - Benefit**

1495 **Score:** Prohibitive **Confidence:** Low

1496 The cost of producing and deploying Ice-Wood panels at scale is not yet known, as
1497 no detailed techno-economic assessment has been published. However, any large-
1498 scale deployment over open Arctic waters would require substantial logistical
1499 resources — including vessel operations in remote and harsh conditions — making
1500 the cost-benefit ratio unfavourable at basin-wide scales. Conversely, targeted
1501 deployment at specific strategic locations, such as sea-ice arch choke points, could
1502 substantially improve the cost-benefit profile by concentrating the intervention where
1503 the climate leverage per unit of effort is highest, at a fraction of the logistical cost of
1504 open-ocean coverage.

1505 **Likelihood of environmental risks**

1506 **Score:** Some risk **Confidence:** Medium

1507 The preprint does not provide any quantitative assessment of the environmental
1508 impacts associated with large-scale deployment of Ice-Wood. It mainly emphasizes
1509 that the material is derived from natural wood via partial lignin removal and surface
1510 carbonization, and therefore presents the concept as an environmentally responsible
1511 alternative to synthetic solutions, but without life-cycle analysis or ecological impact
1512 studies. From an ecological perspective, however, a widespread coverage of the
1513 sea-ice surface with high-albedo wooden panels would inevitably reduce light
1514 transmittance into and through the ice, thereby altering the light regime that
1515 constrains primary production within the ice matrix and in the underlying water
1516 column. The dispersal and eventual degradation of large quantities of wood in the
1517 marine environment would also introduce additional organic carbon, stimulating
1518 microbial respiration and potentially modifying local oxygen dynamics and
1519 biogeochemical cycling. These issues, together with impacts on habitat structure and
1520 higher trophic levels, remain unexplored in the current study and would need to be
1521 rigorously assessed before any consideration of large-scale implementation.

1522 **Effects on local/ indigenous communities**

1523 **Score:** Neutral **Confidence:** Low

1524 Like other techniques involving wood (e.g. Pykrete) little information is available to
1525 assess the impacts of pykrete deployment on local and indigenous communities.
1526 Reinforcing sea ice strength could support ice roads and facilitate ice-based
1527 transportation and hunting. But the potential environmental risk, including reduced
1528 primary production, can have adverse effects on food supply for local communities.

1529 **Ease of reversibility**

1530 **Score:** Hard **Confidence:** High

1531 The reversibility of the Ice-Wood intervention is more limited than that of other wood-
1532 based approaches such as pykrete. Unlike sawdust dispersed into the ice matrix,
1533 which would be released gradually upon melting and degrade relatively rapidly in the
1534 water column, solid wooden panels deployed on or within sea ice would be
1535 extremely difficult to retrieve at scale once distributed across large Arctic ice
1536 surfaces. Should the intervention be discontinued, the physical recovery of panels
1537 would be logistically impractical, and their degradation in the cold, low-productivity
1538 Arctic marine environment would likely proceed over timescales of years to decades,
1539 considerably longer than for dispersed wood pulp. The persistence of wooden panels
1540 in the marine environment also raises concerns regarding long-term ecological
1541 impacts and navigational hazards, further complicating any exit strategy.

1542 **Risk of Termination shock**

1543 **Score:** Low risk **Confidence:** –

1544 The risk of termination shock is low, as the intervention does not create a sustained
1545 forcing whose abrupt cessation would trigger a rapid climatic response. However, the
1546 physical persistence of wooden panels in the marine environment after
1547 discontinuation means that ecological effects — including water column shading and
1548 organic matter inputs — may continue independently for an extended period, as
1549 highlighted in the ease of reversibility assessment.

1550 **Suitability within current legal/ governance structures**

1551 **Score:** Challenging **Confidence:** –

1552 The large-scale deployment of Ice-Wood panels on Arctic sea surfaces currently
1553 lacks any specific international legal or governance framework. Operations in the
1554 High Seas would fall under the United Nations Convention on the Law of the Sea
1555 (UNCLOS), which does not explicitly address deliberate sea-ice engineering
1556 interventions of this nature, and would likely require new multilateral agreements
1557 among Arctic states. Within Exclusive Economic Zones (EEZs), coastal states retain
1558 sovereign rights and could in principle authorise deployments under domestic
1559 legislation, but no such regulatory pathway currently exists. Beyond jurisdictional
1560 questions, the widespread distribution of floating wooden panels across sea-ice
1561 areas would pose significant navigational hazards for vessels operating in Arctic or
1562 fishing, potentially requiring the establishment of dedicated exclusion zones and
1563 mandatory notification procedures under International Maritime Organization (IMO)
1564 frameworks. The eventual degradation or accidental dispersal of panels would
1565 further raise questions under the London Protocol on the prevention of marine
1566 pollution, given the large quantities of organic material introduced into the marine
1567 environment.

1568 **Amount of attention in scientific journals and public media and currently**
1569 **ongoing research programs**

1570 **Score:** Low **Confidence:** –

1571 The Ice-Wood concept has begun to attract some attention in the media and within
1572 specialist geoengineering circles, but has not yet generated broad public exposure
1573 on mainstream social networks. A recent article in New Scientist (Simms 2025).
1574 presents the idea of floating wooden platforms that could enhance the formation and
1575 persistence of sea ice in the Arctic, thereby introducing the concept to a wider
1576 science-interested audience. In parallel, the preprint has been discussed in solar
1577 geoengineering newsletters and weekly summaries, where it is framed alongside
1578 other proposed climate interventions such as stratospheric aerosol injection, cirrus
1579 cloud thinning, and reflective microspheres. These niche outlets indicate that
1580 Ice-Wood is already on the radar of the climate intervention community, but there is,

1581 to date, no evidence of significant visibility or debate on major social media platforms
1582 beyond these specialized discussions

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Draft for Review

Sea Ice growth management

Overall assessment: The sea ice growth management concept, first proposed by Veli Albert Kallio in 2010

(<https://groups.google.com/g/geoengineering/c/XMR75eB77c8/m/aJrf6Zp3okcJ>), has not been substantively explored since its initial suggestion, and no peer-reviewed studies, engineering assessments, or field experiments have been reported. As a result, very little information is available on the nature, materials, and mode of deployment of the cables or levees envisaged, making a thorough evaluation of the approach inherently difficult.

The scalability of the technique is fundamentally limited by the need to anchor structures to the seabed, confining realistic deployment to shallow coastal and shelf areas and excluding the vast majority of the deep Arctic Ocean. As the areal extent of deployed structures increases, the mechanical stresses imposed by sea ice drift and currents would increase considerably, posing inherent structural limits to any upscaling effort. The logistical demands of deploying and maintaining such infrastructure in a remote and harsh Arctic environment are expected to be substantial, raising questions about the overall cost-benefit ratio of the approach.

If the structures were intended to be free-floating rather than anchored, they would constitute unattended drifting objects in navigable waters, which is not permitted under international maritime law — in particular the SOLAS Convention and the COLREGS — as such objects pose an unacceptable navigational hazard. This legal constraint would effectively preclude free-floating deployment in Arctic shipping lanes.

Taken together, the lack of substantive follow-up since the original proposal, the inherent scalability constraints, the logistical complexity, and the unresolved governance questions suggest that this approach, while conceptually interesting as a localised intervention at strategic choke points such as sea-ice arch formation zones, faces significant barriers to development and deployment that would need to be addressed before it could be considered a viable climate intervention.

Issue being addressed

Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.

Description of the technology/ measure

In 2010 Veli Albert Kallio suggested the use of ‘floating cables or levees, even platforms’, to act as ‘seeding points to fasten the seasonal growth of the Arctic Ocean's sea ice.’

1625 (<https://groups.google.com/g/geoengineering/c/XMR75eB77c8/m/aJrf6Zp3okcJ>)

1626 Even if multiyear ice disappeared, he claimed such schemes might be used to
1627 stimulate the growth of ice, which would then lead to thicker ice the next year which
1628 would reflect more sunlight for a longer time.

1629 At first sight, with the exception of the cable deployment itself, this approach appears
1630 to have a limited environmental footprint as it aims to promote sea ice growth, a
1631 natural process occurring at locations where ice would normally form. However, little
1632 information is available on the methods envisioned, and the effectiveness of wire
1633 deployment in triggering or enhancing sea ice formation in the open ocean remains
1634 to be demonstrated. Scaling up such methods would require the deployment of
1635 cables over an unprecedented spatial extent, raising numerous questions regarding
1636 technical feasibility, environmental impacts — including those on marine mammals
1637 and benthic ecosystems — navigational hazards, and the practicability of eventual
1638 retrieval and recovery of the deployed infrastructure

1639 **Technological readiness**

1640 **Score:** Medium

Confidence: Medium

1641 This idea was probably not explored further. Basically any method to create open
1642 spots in autumn and winter produces more ice.

1643 **Scalability**

1644 **Score:** Low

Confidence: High

1645 The scalability of this approach is limited by the requirement to deploy and maintain
1646 cables or levees in fixed positions, which implies the need for anchoring to the
1647 seabed and therefore restricts deployment to relatively shallow coastal or shelf
1648 areas. The complexity of installing and maintaining such infrastructure at sea further
1649 constrains the spatial extent over which the technique could realistically be deployed,
1650 making large-scale coverage of the Arctic Ocean impractical with current technology.
1651 Furthermore, as the aerial extent of the deployed structures increases, the
1652 mechanical stresses imposed on the cables or levees by sea ice drift, currents, and
1653 wave action would increase considerably, posing inherent structural limits to
1654 scalability that become progressively more difficult to overcome at larger scales.

1655 **Timeliness for near-future effects**

1656 **Score:** Medium

Confidence: High

1657 The concept was proposed in 2010 but does not appear to have been pursued
1658 further since, and no dedicated field trials or engineering assessments have been
1659 reported. Given the limited technological readiness and the unresolved questions
1660 surrounding cable deployment, anchoring, and effectiveness in open Arctic waters,
1661 any near-future contribution to Arctic sea ice recovery appears unlikely. Small-scale
1662 pilot experiments in shallow coastal environments could however be envisaged
1663 within the next decade, justifying a medium timeliness rating.

1664 **Potential to make a difference in Northern + Arctic**

1665 **Score:** Low **Confidence:** High

1666 Confinement to shallow coastal and shelf areas excludes the vast majority of the
1667 deep Arctic Ocean, limiting the regional impact of the approach. An exception may
1668 be targeted deployment at strategic shallow choke points, such as sea-ice arch
1669 formation zones, where a localised intervention could yield a disproportionately large
1670 Arctic-scale benefit.

1671 **Potential to make a global difference**

1672 **Score:** Low **Confidence:** High

1673 Given its confinement to shallow areas and the limited spatial extent that can
1674 realistically be treated, this approach is unlikely to produce any measurable effect on
1675 global climate metrics. Even under optimistic assumptions, the total treated surface
1676 area would represent a negligible fraction of the Arctic Ocean, with correspondingly
1677 negligible impacts on global mean temperature or planetary albedo.

1678 **Cost - Benefit**

1679 **Score:** Low **Confidence:** High

1680 The deployment and maintenance of cables or levees in Arctic marine environments
1681 is logistically demanding, requiring specialised vessels, anchoring systems, and
1682 repeated operations in remote and harsh conditions. In the absence of detailed cost
1683 estimates, the overall cost-benefit ratio of the approach appears unfavourable,
1684 particularly given the limited spatial coverage achievable and the correspondingly
1685 modest expected impact on Arctic sea ice.

1686 **Likelihood of environmental risks**

1687 **Score:** Some risk **Confidence:** Low

1688 The likelihood of environmental risks is difficult to assess given the very limited
1689 information available on the nature of the materials to be used, their precise mode of
1690 deployment, and the spatial scale envisaged. However, the deployment of cables,
1691 ropes, or levees on the seabed and in the water column would inevitably introduce
1692 physical structures into the marine environment, with potential environmental
1693 impacts.

1694 **Effects on local/ indigenous communities**

1695 **Score:** Neutral **Confidence:** Low

1696 It is difficult to assess given the lack of information. Any reinforcement of ice can
1697 support ice-based transportation or hunting, but environmental risks need to be
1698 thoroughly assessed as any environmental impact related to food security of
1699 indigenous populations.

1700 **Ease of reversibility**

1701 **Score:** Medium **Confidence:** Low

1702 The intervention is in principle reversible through the physical retrieval of the
1703 deployed cables or levees. However, given the very limited information currently
1704 available on the nature of these structures and their mode of deployment, the
1705 practical difficulty of removing them — particularly after potential entanglement with
1706 sea ice, sediment burial, or structural damage — is difficult to assess. Reversibility is
1707 therefore considered plausible but operationally uncertain.

1708 **Risk of Termination shock**

1709 **Score:** Low risk **Confidence:** High

1710 The risk of termination shock is low. The intervention does not create a sustained
1711 climatic forcing whose abrupt cessation would trigger a rapid compensatory
1712 response. Removing the cables or levees would simply cease the localised effect on
1713 ice growth, allowing the system to return to its natural trajectory without abrupt
1714 transition. Any residual effects would be limited to the local benthic and pelagic
1715 environment in the vicinity of the structures.

1716 **Suitability within current legal/ governance structures**

1717 **Score:** Challenging **Confidence:** Low

1718 The suitability of this approach within current legal and governance frameworks is
1719 difficult to assess given the very limited information available on the deployment
1720 method envisaged. The governance implications depend critically on whether the
1721 structures would be anchored to the seabed or left to drift freely. Anchored
1722 installations in Arctic waters would need to comply with UNCLOS provisions
1723 governing the use of the seabed and the water column, and would likely require
1724 environmental impact assessments and permits under national or international
1725 frameworks depending on the jurisdiction. If, on the other hand, structures were
1726 deployed as free-floating elements, they would constitute unattended drifting objects
1727 in navigable waters, which is not permitted under international maritime law — in
1728 particular the SOLAS Convention and the COLREGS — as such objects pose an
1729 unacceptable navigational hazard to shipping or fishing. This fundamental legal
1730 constraint would effectively preclude free-floating deployment in any waters used by
1731 vessels, including Arctic shipping lanes.

1732 **Amount of attention in scientific journals and public media and currently**
1733 **ongoing research programs**

1734 **Score:** Low **Confidence:** Low

1735 The idea seems not to have been picked up after having been suggested.

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1738 Ice shields and “Volcanoes”

1739 Overall assessment:

1740 This technique alleviates some concerns associated with other ice thickening
1741 techniques which involve bringing seawater to the top of existing ice. As mentioned
1742 in web post, “A significant benefit of the ‘ice volcano’, in comparison to other
1743 proposed geoengineering projects, is that it merely augments a natural activity and
1744 does not introduce any unfamiliar chemicals or processes into the environment”
1745 (https://www.eng.cam.ac.uk/news/undergraduate-project-can-ice-volcano-help-regenerate-sea-ice#:~:text=Katy%20used%20theoretical%20modelling%20and,at%20least%20two%20summers'%20melt.)).
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1749 But this highlights that other techniques introduce unfamiliar biogeochemical
1750 processes, as mentioned by Miller et al. (2020). Having the pumps and the rest of
1751 the system below the water level reduces the risk of freezing of the system. But how
1752 forming these cones will protect the rest of the ice is not clear. They will be prone to
1753 being pushed away by the prevailing winds or currents like icebergs. If they are
1754 drifting offshore, the cones will melt without providing a clear benefit to extend the
1755 ice's lifetime. So the location of the build up of the cones does matter, but can be
1756 selected with a thorough study of sea ice drift in the polar oceans. But existing data
1757 and models allow us to do so. Another concern is the disposal of the pump. If the
1758 pump is not removed and will end up in the sea.

1759 Issue being addressed

1760 Arctic sea ice extent has rapidly decreased over the last few decades, with most
1761 multi-year ice disappearing altogether. This has already had major effects on local
1762 communities and ecosystems. The disappearance of the relatively reflective sea ice
1763 also leads to a dramatic decrease of albedo in the Arctic and subsequent high
1764 energy uptakes by the darker water during the Arctic summers.

1765 Description of the technology/ measure

1766 Similar to other ideas to pump water on sea ice (see sections on Sea Ice Thickening
1767 above), engineer Sev Clarke and engineering student Katy Cartlidge both came up
1768 with designs to artificially produce sea ice. In both schemes, water is pumped up
1769 through a central pipe and allowed to freeze onto previously-grown ice. This ongoing
1770 process then slowly forms a thicker mass of ice that would hopefully be able to
1771 survive over longer periods. Many of these “icebergs”, which Clarke calls Ice Shields
1772 and Cartlidge dubbed ice volcanoes, could together form larger surface areas that
1773 could have multiple benefits for ecosystems and the climate.

1774 Spray techniques might be a more effective way to produce ice. This method was
1775 studied in 1970s and 1980s for oil and gas platform applications.

1776 **Technological readiness**

1777 **Score:** Low **Confidence:** Medium

1778 Both ideas have been suggested by their authors but have not been explored further.

1779 Feasible, but spraying would be more effective (C-CORE 2005).

1780 **Scalability**

1781 **Score:** Medium **Confidence:** –

1782 It is linear.

1783 **Timeliness for near-future effects**

1784 **Score:** Low **Confidence:** –

1785 **Potential to make a difference in Northern + Arctic**

1786 **Score:** Low **Confidence:** –

1787 **Potential to make a global difference**

1788 **Score:** Low **Confidence:** –

1789 **Cost - Benefit**

1790 **Score:** Moderate **Confidence:** –

1791 Hao *et al.* (2023) estimate that the melting of sea ice would cost the world an

1792 average of 6.7–13.3 trillion USD annually over the period 2020 to 2100, when the

1793 costs of the forcing effects of the ice are calculated in terms of equivalent costs of

1794 the forcing that is the result of GHG emissions.

1795 **Likelihood of environmental risks**

1796 **Score:** Some risk **Confidence:** –

1797 If the pump is not removed it will end up in the sea. Potential navigation hazard.

1798 **Effects on local/ indigenous communities**

1799 **Score:** Unknown **Confidence:** –

1800 Risks for local marine traffic.

1801 **Ease of reversibility**

1802 **Score:** Medium **Confidence:** –

1803 May lead to buildup of thickness. Another concern is the disposal of the pump. If the

1804 pump is not removed and will end up in the sea.

1805 **Risk of termination shock**

1806 **Score:** Some risk **Confidence:** –

1807 Ice islands may live long when thick creating a potential navigation hazard.

1808 **Suitability within current legal/ governance structures**

1809 **Score:** Challenging **Confidence:** –

1810 **Amount of attention in scientific journals and public media and currently**
1811 **ongoing research programs**

1812 **Score:** Medium **Confidence:** –

1813 Both ideas are isolated and have not yet been subject to further study.

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Draft for Review

1818 **Snowfall enhancement**

1819 Overall assessment:

1820 This is a feasible way to protect sea ice over the summer by increasing the albedo.
1821 Snowfalls need to be generated in spring to avoid insulation effects. The limitations
1822 are in the moisture content of Arctic air masses. Another possibility is to add snow
1823 accumulation in winter to produce more snow-ice that would become more realistic
1824 when first-year congelation ice becomes thinner.

1825 **Issue being addressed**

1826 With the exception of some regions like Antarctica, global snowfall amount and
1827 frequency have decreased, and the timespan during which snow cover remains has
1828 shortened (Zender 2012). This has multiple effects on human and natural systems
1829 as over sea ice it influences widely diverging processes such as reducing surface
1830 albedo, influencing ice quality and thickness, and changes in the marine ecology due
1831 to impact on light transfer. In the Arctic Ocean, snow cover delays summer melting of
1832 sea ice and supports survival of ice and existence of multi-year ice. Another impact
1833 is the production of snow-ice, which could oppose the thinning of congelation ice.

1834 **Description of the technology/ measure**

1835 There have been sparse references to the use of cloud seeding over Arctic and
1836 Northern areas as a means of countering some of the effects of climate change (see
1837 the topic in Atmosphere section). Some have suggested using it specifically over
1838 glaciers (see Stabilizing Glaciers by Cloud Seeding). Yet, most studies focus on
1839 cloud seeding as a means to ensure water security. Solid precipitation increases the
1840 albedo and the ice and snow volume that support the life of glaciers, seasonal snow
1841 cover, and floating ice. In principle, snow accumulation large enough on floating ice
1842 can trigger snow-ice formation that would increase the produced mass of snow and
1843 ice.

1844 Precipitation enhancement and weather modification has a long history, with the first
1845 modern field trials with the “seeding” of clouds by airplanes starting after WW2. The
1846 idea behind “glaciogenic” cloud seeding is that introducing silver iodide (AgI)
1847 particles into supercooled clouds will encourage nucleation and growth of particle
1848 size, thereby allowing more water to leave the cloud in the form of precipitation.
1849 When the lower layers of atmosphere are cold enough, precipitation falls in snow
1850 crystals on the surface.

1851 Snowfall has the potential to promote sea ice lifetime of the sea thickness, but timing
1852 does matter. Should snowfall occur in fall and winter, the snow cover will reduce heat
1853 transfer through the ice, thereby decreasing ice growth. To increase the summer
1854 albedo, snowfall is best around April–May when congelation ice does not grow any
1855 more, and air is cold to get the precipitation in solid phase. At that time, snow cover
1856 will provide insulation, reduce melting, and maintain albedo, thereby reducing
1857 incoming radiation. However, if the precipitation occurs during positive temperatures,

1858 then the precipitation will shift towards rainfall, with adverse effects on the ice cover.
1859 Rainfall will decrease the protective snow cover and will bring heat to the ice surface,
1860 enhancing the sea ice melt. However, there is another impact of snow accumulation,
1861 snow-ice formation. This is common in Antarctic seas but less in the Arctic where
1862 congelation ice is still too thick to allow flooding of sea ice. In a warmer Arctic the
1863 situation would be different.

1864 **Technological readiness**

1865 **Score:** High **Confidence:** Low

1866 The history of research into weather modification is quite expansive, and saw
1867 significant expansion in the second half of the twentieth century (Fleming 2010). The
1868 technology already exists and is being used commercially around the world,
1869 especially to encourage rainfall. However, the main and longstanding issue with
1870 snow enhancement experiments is that it is extremely difficult to show whether
1871 specific cloud seeding missions resulted in a significant increase in snowfall, or if this
1872 was already expected to fall without any active seeding action (Geerts *et al.* 2010;
1873 Geerts and Rauber 2022). In cloud seeding circles, belief in the potential of the
1874 technology has always been strong (see for example Huggins 2009 or most other
1875 articles in the main weather modification journal *The Journal of Weather*
1876 *Modification*), and promises that definite proofs would be delivered within years have
1877 been often repeated since the 1970s (Fleming 2010). More recently there has again
1878 been much excitement in the cloud seeding community as a combination of several
1879 measurement advances may finally be able to definitively prove the effect of seeding
1880 (Friedrich *et al.* 2020).

1881 There have been several major studies in the US, such as the Seeded and Natural
1882 Orographic Wintertime Clouds – the Idaho Experiment (SNOWIE), but the most
1883 expansive study with glaciogenic seeding was The Wyoming Weather Modification
1884 Pilot Program which ran from 2005 to 2014 (NCAR n.d.). The project initially reported
1885 major precipitation increases, although a statistical evaluation study four years later
1886 found that the project was not statistically significant as it had failed 'to reject the null
1887 hypothesis that there is no seeding effect' (Rasmussen *et al.* 2018).

1888 **Scalability**

1889 **Score:** Low **Confidence:** Low

1890 Cloud seeding can only be done if the right clouds are present, and even if seeded,
1891 there is only a limited amount of potential extra precipitation to be gained from
1892 specific clouds. This limitation is exacerbated by the requirement for extensive
1893 seeding infrastructure which would need enormous investments in the sparsely
1894 populated and isolated Northern and Arctic regions. This would make it difficult to
1895 scale up such a measure without enormous investments.

1896 **Timeliness for near-future effects**

1897 **Score:** Low **Confidence:** Low

1898 The technology for glaciogenic cloud seeding already exists, but it is not sure if it
1899 would be able to make a significant climate impact, even if it would be sufficiently
1900 scaled up. For sea ice albedo increase to delay sea ice melting, solid precipitation
1901 would be most effective in spring.

1902 **Potential to make a difference in Northern + Arctic**

1903 **Score:** Low **Confidence:** High

1904 Cloud seeding could have major effects on water availability, yet its specific climate
1905 effects are very much understudied. Given the difficulties around scalability, it seems
1906 unlikely that snowfall over the entire regions could be enhanced significantly,
1907 although local applications on specific glaciers could be more feasible (see
1908 Stabilizing Glaciers by Cloud Seeding). In the Arctic Ocean, the extent of multi-year
1909 ice could become significantly larger.

1910 **Potential to make a global difference**

1911 **Score:** Low **Confidence:** High

1912 The seeding would likely have a primarily local and regional effect.

1913 **Cost - Benefit**

1914 **Score:** Prohibitive **Confidence:** Low

1915 Cloud seeding is likely relatively expensive to do at scale, with the project in
1916 Wyoming reporting low estimates of '\$27 to \$214 per acre-foot and higher costs
1917 ranging from '\$53 to \$427 per acre-foot.' So although it might be financially feasible
1918 for areas with particularly high water prices, or in specific glacial regions, large-scale
1919 seeding across large areas is likely to be prohibitively expensive.

1920 **Likelihood of environmental risks**

1921 **Score:** Low Risk **Confidence:** High

1922 The seeding material, AgI, has been used in experiments for a long time and has not
1923 been subject to much criticism. A main environmental effect of extensive seeding is
1924 related to changes in the hydrological cycle, as increases in precipitation over one
1925 area will likely lead to reductions over another.

1926 **Effects on local/ indigenous communities**

1927 **Score:** Neutral **Confidence:** Low

1928 If employed in spring (thought best to increase summer albedo) enhanced snowfall
1929 could be positive for surface travel by coastal communities, and it could benefit
1930 survival of ringed seal pups in their subnivean dens. If the increase precipitation

1931 occurred as rain, however, the effects on travel and seal productivity would be
1932 negative.

1933 **Ease of reversibility**

1934 **Score:** Easy **Confidence:** Low

1935 The effects of this measure cease after each application when the generated snow
1936 has melted.

1937 **Risk of termination shock**

1938 **Score:** Low Risk **Confidence:** High

1939 Because the snow would melt over time, seeding would need to be actively
1940 continued. After termination, a snow layer would return to equilibrium in a time scale
1941 of one year.

1942 **Suitability within current legal/ governance structures**

1943 **Score:** Possible **Confidence:** Low

1944 Cloud seeding is already practiced by companies and states around the world. The
1945 main provision is that it cannot be used for military purposes following the 1977
1946 Environmental Modification Convention. Some commentators warn cloud seeding
1947 could lead to major geopolitical tension around water redistribution in the future
1948 (Chien et al. 2017; Shevchenko and Horiacheva 2021; de Guglielmo 2021).

1949 **Amount of attention in scientific journals and public media and currently**
1950 **ongoing research programs**

1951 **Score:** Medium **Confidence:** High

1952 Weather modification has been a relatively niche topic over the last several decades
1953 as successes failed to materialize. However, it is gaining increased global attention
1954 due to the increasing amounts of droughts. Interest seems to be especially great in
1955 China, Australia, the US, and countries in the Arabian peninsula.

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1965 **Sea ice generation by icebreaking in winter**

1966 Overall assessment: The idea is to increase winter heat loss from the Arctic Ocean
1967 to produce more sea ice volume. The method is icebreaking in winter, which results
1968 in more ice due to opening of leads and formation of rafted ice and ridges. Thick
1969 ridges can survive over summer.

1970 **Issue being addressed**

1971 Sea ice is a thin layer between the atmosphere and the ocean with a large impact on
1972 the transfer of heat, momentum, and matter between these media. In winter its very
1973 low thermal conductivity, as compared with the turbulent conductivities of air and
1974 seawater, reduces ice growth as the ice insulates itself. Opening the ice cover leads
1975 to high growth rate, as naturally occurs in leads opened by the wind. Thus, further
1976 opening by icebreakers creates more ice than in the natural growth cycle.

1977 **Description of the technology/ measure**

1978 There have been occasional undeveloped references to the idea to break up sea ice
1979 in winter with icebreakers to increase the amount of deformed ice. In the 1980s it
1980 was estimated by modelling that 1% lead opening in the Arctic would double the heat
1981 loss that would result in more ice production.

1982 Considering only the opening of sea ice cover by icebreakers, intensive growth of
1983 new ice would result since the upper ocean layer is at the freezing point temperature.
1984 Breaking sea ice using icebreakers produces open spots where ice growth can be
1985 fast. The growth rate of bare ice is inversely proportional to ice thickness. Thus, thin
1986 ice grows 5–10 times faster than thick ice. The broken ice floes removed from the
1987 open water spots are pushed above or below the existing ice and increase the
1988 thickness there. This extra ice will mean a larger volume of sea ice survival over
1989 summer with larger albedo effect, and there will be more multi-year sea ice in the
1990 following winter. Also, breaking sea ice would increase radiative (and turbulent) heat
1991 losses from the ocean to the atmosphere in winter and oppose global warming.
1992 This seems to be perfectly feasible, but it should be coupled with conventional
1993 icebreaking operations.

1994 **Technological readiness**

1995 **Score:** Low **Confidence:** Low

1996 Ice breaking would produce more ice due to accumulation of ice blocks (ridges) while
1997 increasing the heat loss. This would increase summer albedo and lead to more multi-
1998 year ice.

1999 **Scalability**

2000 **Score:** Medium **Confidence:** Low

2001 Effectivity is proportional to the number of icebreakers used.

2002	Timeliness for near-future effects	
2003	Score: Medium	Confidence: Low
2004	Icebreaking would need a fleet.	
2005	Potential to make a difference in Northern + Arctic	
2006	Score: Medium	Confidence: Low
2007	Adding the volume of multiyear ice is specially important for Arctic to save ice.	
2008	Potential to make a global difference	
2009	Score: Low	Confidence: Low
2010	No significant effect expected.	
2011	Cost - Benefit	
2012	Score: Moderate	Confidence: Low
2013	The process would need to be repeated at regular intervals, both within winter and interannually.	
2014		
2015	Likelihood of environmental risks	
2016	Score: Some risk	Confidence: Low
2017	Effects of breaking ice would severely endanger local ecosystems. The warming in the Arctic due to increased outgoing radiation and turbulent losses could create problems for the region.	
2018		
2019		
2020	Effects on local/ indigenous communities	
2021	Score: Negative	Confidence: Low
2022	Surface travel on sea ice is vital to Indigenous harvests of whales, walruses, seals, sea birds, and fish across much of the Arctic. In the North American Arctic, Indigenous communities express considerable alarm over ice breaking in the areas they harvest.	
2023		
2024		
2025		
2026	Ease of reversibility	
2027	Score: Medium	Confidence: High
2028	Arctic sea ice cover would return to its natural state in a few years.	
2029	Risk of Termination shock	
2030	Score: Low risk	Confidence: High
2031	If re-stratification is possible, the time scale is decades and impacts unclear.	

2032 **Suitability within current legal/ governance structures**

2033 **Score:** Challenging **Confidence:** Low

2034 The sea ice within the Exclusive Economic Zone of individual countries may be
2035 modified under domestic laws, e.g., by the river freshwater outflows.

2036 **Amount of attention in scientific journals and public media and currently**
2037 **ongoing research programs**

2038 **Score:** Low **Confidence:** Low

2039 Indirectly seen in some modeling studies.

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