

Executive Summary

Safeguarding the polar regions from dangerous geoengineering

Geoengineering approaches have gained increasing attention as proposed solutions to reduce the adverse effects of climate change, especially impacts from polar regions such as sea-level rise and permafrost thaw emissions. This scientific assessment, by 42 leading polar and climate scientists, evaluated five proposed geoengineering concepts that focus on polar action. The assessment concludes that these methods are unlikely to work in avoiding climate impacts, would have potentially severe and unpredictable environmental and societal impacts, and would be prohibitively expensive or unfeasible in harsh polar conditions. It concludes that research efforts are better focused on decarbonising and, in the polar regions, on fundamental research that will underpin detailed understanding of processes driving observed and projected changes.

The assessment reviews the following five proposed concepts:

- Stratospheric aerosol injection to increase reflection of the sun's rays within the atmosphere to reduce warming temperatures
- Construction of sea curtains to divert warm ocean water away from the margins of ice sheets to reduce melting and resulting sea-level rise
- Whitening sea ice to increase its reflectivity and thickening it to increase its longevity, reducing sea ice losses and increasing the cooling impact of the Arctic Ocean
- Removal of water from beneath fast-flowing regions of the polar ice sheets to slow down their flow into the ocean
- Addition of iron to ocean water to increase biological CO₂ drawdown from the atmosphere

The assessment evaluates these concepts based on five criteria: 1) effectiveness and feasibility, 2) risks and unintended consequences, 3) cost and scale, 4) governance, and 5) timing and ethics.

Based on these criteria, using an extensive review of published scientific literature, the assessment concludes that the five concepts:

- Would have negative consequences both within and beyond the polar regions
- Their efficacy is at best highly uncertain given the complexity of the Earth System
- By not addressing the root cause of climate change (greenhouse gas emissions), they do not stop ocean acidification or other non-temperature-related highly damaging impacts
- Their implementation and sustained maintenance are prohibitively expensive
- The technological and logistical challenges are prohibitive given the remote and extreme environments of polar regions, especially given the required scale
- They face far greater governance challenges than already exist in the Paris Agreement context, especially in an era of geopolitical instability
- They fail to address key environmental protection concerns, as set out in existing governance frameworks
- Ethical challenges arise in polar regions where their implementation would directly impact the environment of indigenous communities
- They distract and delay attention from urgent decarbonization, giving false hope and narrowing feasible remaining carbon reduction pathways.

The paper notes deep concern about the increasing prevalence of proposals to apply these dangerous concepts as a “quick fix to buy time”. It concludes instead that these proposed interventions fall on the maladapted end of the spectrum of options to address climate change.

The only realistic and effective means to effectively protect the climate system and limit impacts from the loss of the frozen regions of the planet remains rapid and sustained decarbonization to net zero within the next two-three decades, with adaptation to current and future global impacts from deterioration of polar regions.

This detailed review of these five geoengineering concepts can be found in the peer-reviewed *Safeguarding the Polar Regions from Dangerous Geoengineering: A Critical Assessment of Proposed Concepts and Future Prospects*, published in *Frontiers in Science*.

Policy Brief published on 03/11/2025, <https://doi.org/10.5281/zenodo.17488507>

Introduction and Background

Global warming is increasing the frequency and intensity of climate extremes and their impacts. The polar regions contain the majority of Earth's potential tipping points and are warming at several times the global average rate. These regions are experiencing rapid change that can profoundly disrupt the Earth's climate system. In the Arctic, severe loss of sea ice area and thickness, permafrost thaw, and widespread ecosystem disruption is threatening infrastructure and the livelihoods of Indigenous and local communities. Permafrost thaw also has led to increasing CO₂ and methane emissions. Accelerating ice loss from Antarctica and Greenland means that these vast ice sheets, combined, are now the largest contributor to global sea-level rise. Polar oceans have absorbed more than half of the carbon taken up by the world's oceans, resulting in high rates of acidification and harming the wider food web. Increased freshwater input from the melting ice sheets and sea ice, alongside polar ocean warming are disrupting ocean circulation alongside polar marine ecosystems, with serious implications for global climate stability.

Despite these threats, we are currently on a knife's edge of exceeding 1.5°C within a few years, and 2.7°C by 2100.¹ The collective failure to adequately reduce carbon emissions has led to a surge in geoengineering concepts framed as “buying time”, to lessen the impacts of temperature overshoot. In this policy brief, we refer to geoengineering² as the technological manipulation of the atmosphere, oceans, sea ice, and/or ice sheets in an attempt to reduce the impact of increasing global mean temperatures. We do not include carbon dioxide removal technologies or practices via Nature-based Solutions or by technical means in our definition of geoengineering.

The peer-reviewed paper published in *Frontiers of Science*³ provides an in-depth expert analysis of the five most prevalent polar geoengineering concepts, with these fact sheets providing an overall summary for policy makers.

About the authors

The authors of the peer-reviewed scientific assessment article, “**Safeguarding the Polar Regions from Dangerous Geoengineering: A Critical Assessment of Proposed Concepts and Future Prospects**,” published in *Frontiers in Science*, September 9, 2025, include polar and climate scientists from many different disciplines, research institutes and universities. Many have served as Lead Authors or Coordinating Lead Authors on various IPCC reports.

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¹ <https://climateactiontracker.org/global/cat-thermometer/>

² Other terms include “climate repair”, “emergent climate technologies”, and “climate intervention”.

³ <https://doi.org/10.3389/fsci.2025.1527393>

Policy Recommendations: Existing and effective solutions

- The most efficient and effective way to slow global warming, stabilize our climate and limit the impacts of climate change remains rapid and sustained decarbonization and carbon drawdown, reaching net zero CO₂ emissions within the next two-three decades.
- Research and financing should focus on the necessary proven approaches that will bring us to net zero as outlined in IPCC assessments.
- Accelerate the adoption and deployment of clean technologies in multiple sectors (especially transport and energy production) which are already entering a phase of rapid adoption, where costs exponentially fall and efficiency improves.
- Innovation is needed; but rather than direct limited resources towards geoengineering technologies, support for new low-carbon technologies and carbon dioxide removals should be prioritised.
- In addition, strengthen carbon sinks through Nature-based Solutions that carry many economic, health, social and environmental co-benefits such as improved air quality, reduced dependence on carbon imports and reduced exposure to geopolitical conflict. These techniques also restore and protect biodiversity.
- Increase efficiency and economic incentives for technologies and measures on the demand side; these incentives have efficacy to work quickly and come with local and regional economic benefits.
- Integrate climate-resilient development practices to achieve successful adaptation, mitigation and sustainable development through an integrated approach to major economic sectors (energy, transport, manufacturing, land use systems, food systems, and more).
- Available public research funding for polar regions should be focused on developing a deeper understanding of polar systems and monitoring of potential tipping points, especially related to ice sheets and sea-level rise, polar ocean current disturbances and permafrost thaw, to minimize and manage associated risks.

Note: The materials in this policy brief are taken from the extensive assessment contained in the peer-reviewed paper, "Safeguarding the polar regions from dangerous geoengineering: a critical assessment of proposed concepts and future prospects", *Frontiers in Science*, 09 September 2025. Content of this policy brief has been approved by the co-authors. For more information and references, please see the original open-access paper at <https://doi.org/10.3389/fsci.2025.1527393>

Stratospheric Aerosol Injection (SAI)

BACKGROUND

Greenhouse gases in the atmosphere trap solar energy. With the greenhouse effect, their accumulation due to industrial and other human activities, especially the use of fossil fuels, has contributed to the majority of the current increase in global temperatures.

“Aerosols” refers to small, suspended particles in the atmosphere. Some lighter-colored aerosols, especially sulfates, can reflect incoming solar radiation, resulting in a net cooling effect. This cooling effect however is not the same as reducing the greenhouse effect: the Earth system responds differently.

Volcanic eruptions, which contain large amounts of sulfate emissions, already inform our knowledge of these effects. Most recently, in 1991 Mount Pinatubo emitted large amounts of sulfates into the stratosphere. While cooling global mean temperature by 0.5°C for two years, this also resulted in severe weather disruption, such as disturbance of South Asian monsoon rains. Sulfate pollution from use of coal were also responsible for acid rain damage to forests in Europe and North America until scrubber technology eliminated them from power plants in the 1980s.

Proposed Geoengineering Concept



Stratospheric aerosol injection (SAI), sometimes grouped under the term “solar radiation modification” (SRM), entails continually injecting high concentrations of sulfates into the stratosphere to reflect sunlight and artificially cool the planet.

EXPERT EVALUATION: *Environmentally damaging, negative and unpredictable unintended consequences, significant global governance and feasibility challenges*

FEASIBILITY

- Requires sustained global-scale injection of sulfates into the stratosphere to avoid “termination shock” (rapid rise in temperature within 1-2 decades should injection halt for any reason, see below)
- Fleet of needed delivery vehicles exceeds technological capacity
- Estimated costs conservatively reach \$1.7 billion/year, excluding monitoring or liability, maintained for decades and centuries to avoid termination shock

UNINTENDED CONSEQUENCES

- Creates a fundamentally different, artificial climate with new regional risks and extremes
- Highly unpredictable and non-uniform changes in atmospheric circulation, regional precipitation and regional temperatures
- Interference with seasonality, reduced rainfall, disrupting water availability for agriculture, biodiversity, food security
- Reduced incoming solar radiation negatively impacts crop growth and yields.
- Reduced solar energy production
- Could worsen stratospheric ozone depletion, with adverse effects on human health and ecosystems; inhalation of sulfuric acid aerosols could cause respiratory health issues, leading to increased healthcare costs
- Increased ocean acidification beyond critical levels for shelled life, especially in high latitude fisheries
- “Termination shock”: sudden cessation of SAI would lead to rapid temperature spike within a decade or two, far faster than greenhouse gas warming and presenting a significant challenge for adaptation.

GOVERNANCE CHALLENGES

- Legal challenges of liability and compensation, such as fisheries loss from ocean acidification, forestry losses from acid rain or increased crop stress
- No international regulatory framework to manage or monitor deployment: creation of such a framework far more complicated than any existing environmental agreement
- Risk of “rogue actors”: requires a high level of geopolitical stability not existing today

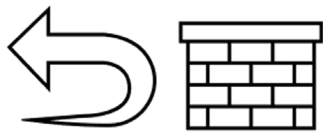
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Sea curtains to block warm water

BACKGROUND

The Antarctic Ice Sheet and some parts of the Greenland Ice Sheet are surrounded by ice shelves – floating platforms of ice that act as natural barriers to slow the movement of the ice sheets or outlet glaciers behind them towards the ocean. Warming ocean waters are accelerating the melting of these ice shelves, causing them to become thinner and more prone to collapse, reducing their slowing effect on the much larger ice sheets they hold back. Continued reductions in ice shelf stability will therefore cause greater ice sheet loss, and global sea levels to rise faster.

Proposed geoengineering concept



Prevent warm ocean water from reaching the ice shelves and margins of the Antarctic and Greenland ice sheets. The concept proposes to attach flexible underwater barriers (sea curtains) to the seafloor in front of ice shelves to block warm ocean water and slow ice loss. The main focus has been on a sea curtain in one part of West Antarctica (offshore Thwaites Glacier) that would be 80 km long, 150 to 500 meters high and installed in waters 600 to 1000 meters deep.

EXPERT EVALUATION: *Not feasible, costly, and environmentally damaging*

FEASIBILITY

- Installation would be immensely challenging due to harsh polar conditions and the remoteness of target sites. Very few ice-strengthened ships can transport such large structures, and even those often struggle in the hazardous, near-impenetrable sea ice. For example, over the 40 years that scientific expeditions have targeted the region where curtain installation is proposed (Amundsen Sea), 56% of expeditions were disrupted or blocked by thick sea ice or had significant difficulty entering or exiting the area. 22% were entirely unable to access the region.
- Barriers would be vulnerable to strong currents or failure of foundations which could compromise the entire structure.
- Computer models have shown that even if installed despite the above extreme difficulties, curtains would at best slow ice loss in Antarctica, not stop or reverse it.
- Underwater barriers would be less effective in Greenland because melting due to warming air temperatures is a major additional driver of ice loss there.
- Conservative cost estimates for an 80 km-long barrier are up to US \$80 billion, highlighting the immense challenge of scaling around Antarctica's 1000s of kilometres of coastline. Real-world analogues in far less harsh environments have exceeded \$6 billion per kilometre (e.g., Thames Barrier, UK). Building ice-strengthened ships to install the curtains would require up to an additional \$1 billion per vessel, and these numbers are likely best-case scenarios that do not include recurrent costs of maintenance or reparation for unintended consequences.

UNINTENDED CONSEQUENCES

- Sea curtains are likely to have far-reaching detrimental side effects on ocean circulation, sea ice formation, marine ecosystems and fisheries, and carbon drawdown.
- Even if successful in blocking water to one region, the barriers could deflect warm water to other sensitive areas of the ice sheet, increasing losses elsewhere.
- Barrier installation and maintenance would release pollution and risk introducing invasive species. The transportation, installation and maintenance of any structure over decades would also have a high carbon footprint. The lifespan of curtain structures has been estimated at 25 years, and degradation could cause pieces to become dislodged over time, posing a severe threat to marine life and shipping.

GOVERNANCE CHALLENGES

- Sea curtains are unlikely to comply with Antarctic Treaty and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) regulations that require international consensus and rigorous review of environmental impacts. Installations around the Greenland Ice Sheet would require permission from the sovereign state of Greenland.

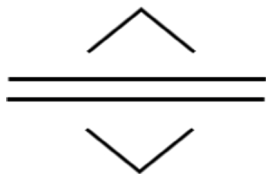
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Modifying the thickness and reflectivity of sea ice

BACKGROUND

Sea ice cools the Earth by reflecting solar energy back out to space. Loss of polar sea ice in recent years has made the Earth's surface less reflective, leading to increased global warming. Continued sea ice decline risks accelerating warming of the polar regions leading to greater permafrost thaw and ice sheet melt, increased threats to polar ecosystems and Indigenous livelihoods, and disrupting key weather systems and ocean currents. At least one sea-ice free summer is expected to occur in the Arctic by 2050, possibly even sooner.

Proposed geoengineering concept



Two geoengineering approaches have been suggested to attempt to preserve sea ice: (1) pumping seawater onto the ice surface during winter to increase its thickness and longevity in the summer, and (2) artificially whitening sea ice by scattering reflective glass microbeads on its surface.



EXPERT EVALUATION: *Unscalable, costly, and environmentally dangerous*

Sea ice thickening

- An estimated 10 million pumps would be needed to cover 10% of the Arctic Ocean, and 100 million to cover the entire Arctic. One million pumps would need to be deployed each year to cover just 10% of the Arctic within a 10-year period, which appears logistically impossible. Given its rapid rate of current decline, sea-ice thickening is simply not feasible at a scale and rate that would have a meaningful effect on sea ice protection
- Producing and installing pumps for 10% of the Arctic Ocean has been estimated to cost \$50 billion per year. The pumps would drift on the sea ice, requiring an unprecedented level of human presence in the High Arctic to conduct year-round maintenance over a large area. The pumps would sink when the sea ice melts or breaks up, littering the seafloor with debris and causing widespread pollution
- Ocean currents and surface winds would cause the pumps and sea ice to drift across sovereign boundaries in the Arctic Ocean. The international legality of a single nation introducing an environmental disturbance into another is a serious issue that would potentially lead to regional tension, disputes and conflict over environmental damage.

Sea ice whitening (spreading glass beads)

- Recent scientific studies have shown that spreading glass microbeads may actually have a net warming effect on Arctic sea ice as they are less reflective than fresh snow. The beads therefore risk absorbing greater amounts of solar energy, accelerating sea ice loss rather than preserving it.
- There are significant concerns that glass microbeads will pose an ecotoxicological risk to polar ecosystems. One recent project (www.arcticiceproject.org) was shut down after ecotoxicological tests revealed potential risks to the Arctic food web. Changes to natural ecosystems will directly impact Arctic Indigenous communities who depend on them. The beads may also change ocean chemistry when they dissolve.
- Massive quantities of beads would be required to cover an effective area of Arctic sea ice. A recent study estimated that around 360 million tonnes per year, an amount equivalent to the annual global production of plastic, would be needed. Production of such a large number of beads would strain global supply chains, and their manufacturing would release a large quantity of carbon emissions.
- The release and transport of glass beads across sovereign boundaries would face the same international legal challenges as outlined for Sea Ice Thickening (above).

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Draining water from beneath ice sheets to slow ice loss

BACKGROUND

The fastest moving regions of the Greenland and Antarctic ice sheets are often lubricated at their base by a thin, pressurized layer of water between the ice and underlying bedrock or sediments. These fast-flowing regions transfer large amounts of ice into the ocean, which contributes to sea-level rise.

Proposed geoengineering concept



Slow the flow of ice into the ocean from the Greenland and Antarctic ice sheets by increasing the friction between the ice and the substrate beneath. Proposed methods include drying the base of the fast-flowing ice sheet regions by pumping water from beneath the ice to the surface; cooling the sediment beneath the ice to promote freeze-on so it “sticks” to the substrate; and/or constructing artificial obstacles beneath the ice to slow ice flow.

EXPERT EVALUATION: *Scientifically flawed, environmentally damaging, and unlikely to be effective*

FEASIBILITY

- **Spatial scale:** Drilling to the base of an ice sheet, which can be hundreds of meters to kilometres thick, is a monumental undertaking necessitating advanced equipment and expertise. A never-attempted-before number of boreholes would be required for even a single glacier. This would be on a scale unprecedented in the history of polar fieldwork, and virtually impossible to execute based on past and current failures of similar expeditions in the field.
- **Duration:** Subglacial water is constantly produced, and frequently shifts location. The sliding of ice would continuously move the drill holes needed for water extraction away from the target sites, breaking the connection within days to weeks. Drill holes would need to be kept open continuously, requiring year-round operations in extremely remote, cold and windy conditions that may be beyond the capabilities of existing technologies.
- Operations in Greenland would also have to deal with massive volumes of surface meltwater produced in summer, requiring constant infrastructure maintenance.
- **Cost:** The cost of such a sustained operation would be immense; a scientific program in 2012 (Subglacial Lake Ellsworth) attempted but failed to keep a single 3 km-deep drill hole open for 24 hours, and cost approximately US \$18 million.

UNINTENDED CONSEQUENCES

- **Water rerouting:** Even in the hypothetical case where water drainage successfully slowed ice flow in a particular area, basal water would be diverted into neighbouring regions, accelerating ice flow elsewhere.
- **Unintended acceleration:** In the unlikely case that large-scale slowdown of the ice was successful, there is a substantial risk that reduced ice flow to the ocean would tip unstable regions of the ice sheet into rapid retreat.
- **Contamination:** The ecosystems underneath the polar ice sheets represent pristine and poorly understood environments. The introduction of a multitude of drill holes risks contamination both below and above the ice.
- **Pollution:** Kerosene is currently the most viable power source in remote field locations. The widespread operation of kerosene generators risks depositing black carbon on the ice surface, darkening the ice and making it more vulnerable to melting.

GOVERNANCE CHALLENGES

- **Antarctic Treaty:** The high level of uncertainty and environmental risk associated with such widespread drilling operations in Antarctica are unlikely to meet the Antarctic Treaty’s strict environmental protection standards.

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Ocean fertilization to increase CO₂ drawdown

BACKGROUND

Over 25% of CO₂ emissions between 2014–2023 were absorbed by the ocean, and some of that was used by phytoplankton for photosynthesis in surface waters. Once these organisms die, they sink as a crucial part of the Earth's carbon cycle. Only a small fraction (less than one percent) makes it to the bottom muds of the deep ocean, where that carbon may be stored for hundreds to thousands of years; the rest however is recycled in much shorter time periods.

Proposed geoengineering concept



Adding micronutrients (such as iron) to ocean waters to stimulate phytoplankton growth, has been proposed to increase the drawdown of CO₂ from the atmosphere into the ocean. The Southern Ocean is viewed as a prime target for artificial fertilization because its waters otherwise have abundant major nutrients (e.g., nitrogen) available for phytoplankton growth, but limited iron. Ocean fertilization is the only geoengineering technique that has been tested directly in the Southern Ocean, with 19 field trials conducted globally to date, with inconsistent results.

EXPERT EVALUATION: *Difficult to scale or govern; environmentally damaging; scientific field trials have been inconclusive*

FEASIBILITY

- The scientific trials of this technique have been inconclusive. Only one trial in the Southern Ocean found increased short-term carbon export to the deep ocean, while long-term carbon storage did not increase in several other trials.
- The technique would be extremely difficult to scale, fertilizing an area of ocean the size of Asia to be globally effective. This would require the creation of a specialised fleet of ships, new docks to deposit iron, and a supply of suitable iron sources for fertilization. None of this infrastructure exists at present.
- Estimates suggest that ocean fertilization could cost up to USD \$1000 per ton of CO₂ removed offshore. For reference, global CO₂ emissions from fossil fuels were around 37.4 billion tonnes in 2024, and the market price of abated carbon currently is well below USD \$100 per ton.

UNINTENDED CONSEQUENCES

- Ocean fertilization may yield unpredictable results as there is no control over which species or groups of phytoplankton are stimulated. Some species may benefit while others are harmed. These changes could impact the Southern Ocean food web, affecting biodiversity and fisheries.
- Fertilization also risks triggering rapid growth and decay of organisms, leading to deoxygenation of ocean waters and the increased production of potent greenhouse gases such as methane and nitrous oxide. Greater uptake of nutrients in the polar oceans could restrict the amount of nutrients exported to lower latitudes, triggering cascading damage to economically and socially important fisheries in the tropical Pacific.

GOVERNANCE CHALLENGES

- Field tests are currently restricted to only legitimate scientific research under the London Convention. No large-scale ocean fertilization projects are currently permitted. The UN Convention on Biological Diversity does not support ocean fertilization, and the Kyoto Protocol states that this technique cannot be used as a carbon credit mechanism. Implications for the Antarctic Treaty and its Convention for the Conservation of Antarctic Marine Living Resources remain unresolved.

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