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Safeguarding the polar regions from dangerous geoengineering: a critical assessment of proposed concepts and future prospects

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Abstract

Fossil-fuel burning is heating the planet with catastrophic consequences for its habitability and for the natural world on which our existence depends. Halting global warming requires rapid and deep decarbonization to "net zero" carbon dioxide (CO_2) emissions, which needs to be achieved by 2050 if warming is to remain within the limits set out by the 2015 Paris Agreement. However, some scientists and engineers claim that a mid-century decarbonization target will not be reached, and they propose that we should focus on technological geoengineering "fixes" or "climate interventions" that could delay or mask some of the impacts of global warming. They often cite the need to slow warming in polar regions because they are experiencing rates of warming higher than the global average, with severe and irreversible projected consequences both locally (e.g., on fragile ecosystems) and globally (e.g., on sea level). Several geoengineering concepts exist for polar regions, but they have not been fully examined by the polar science community, nor integrated with an understanding of polar dynamics and responses. Here, we evaluate five of those polar geoengineering concepts and highlight the significant issues and risks relating to technological availability, logistical feasibility, cost, predictable adverse consequences, environmental damage, scalability (in space and time), governance, and ethics. According to our expert assessment, none of these geoengineering ideas pass scrutiny regarding their use in the coming decades. Instead, we find that the proposed concepts would be environmentally dangerous. It is clear to us that the assessed approaches are not feasible, and that further research into these techniques would not be an effective use of limited time and resources. It is vital that these ideas do not distract from the priority to reduce greenhouse gas (GHG) emissions or from the critical need to conduct fundamental research in the polar regions.

KEYWORDS

global warming, sea level rise, decarbonizing, geoengineering, governance, Arctic, Antarctic, polar

Key points

- Five geoengineering concepts proposed for the polar regions fail to meet the essential criteria required for them to be considered responsible approaches toward limiting the escalation of climate-related risks. These criteria include feasibility and likelihood of success.
- Geoengineering in sensitive polar regions would cause severe environmental damage and comes with the possibility of grave unforeseen consequences.
- Polar regions have complex environmental protection and governance frameworks that would probably reject polar geoengineering fieldwork and large-scale projects.
- Polar geoengineering would require hundreds of billions of dollars in initial costs, plus decades of ongoing maintenance, both of which are presently unavailable and highly unlikely to be secured over necessarily short timescales to address climate change.
- Geoengineering could be used by bad actors as a strategy to create the illusion of a climate solution without committing to decarbonization.
- Minimizing risk and damage from climate change is best achieved by mitigating its causes through immediate, rapid, and deep decarbonization, rather than attempting interventions in fragile polar ecosystems.

Introduction

The burning of fossil fuels and the resulting global warming are unequivocally damaging the polar regions. Human-caused global warming reached 1.3°C above the preindustrial level in 2023 (1, 2) and, in annual terms, over 1.5°C in 2024 (3). The Arctic is currently warming three times faster than the global average (4), resulting in the unprecedented loss of sea ice extent and volume (5, 6), changes in snow duration and extent (7), widespread permafrost thaw (8), glacier retreat (9), accelerating Greenland ice loss (10), increasing wildfires (11), changing vegetation distributions (12), and other profound ecosystem changes. These changes are already affecting the daily lives of Indigenous and local communities that rely on local-to-regional resources (13). Across Antarctica, the average atmospheric warming rate is twice the global average (14). Over the past two decades, ice shelves along some of the Antarctic periphery have collapsed (15). The West Antarctic Ice Sheet is experiencing accelerating mass loss (10) and record-high temperatures have been observed in the Antarctic Peninsula (16) and over the East Antarctic plateau (17, 18). Record lows in Antarctic sea ice extent have also been observed in recent years (19, 20). These changes are harming marine and terrestrial species, ecosystems, and ecosystem services across the Antarctic and Southern Ocean, and these effects are projected to worsen (21–23).

Polar environments provide substantial and important services and benefits to humanity (24): changes here have far-reaching implications for the entire planet. Global sea level rise is accelerated by land ice loss from mountain glaciers and the Greenland and Antarctic ice sheets (10, 25). Additionally, the polar regions influence the global climate through extreme weather events, disruptions to the global ocean circulation, carbon cycling, ocean acidification, and other feedback mechanisms (26). The large, bright surfaces of sea ice and ice sheets reflect over 50% of incoming solar radiation back into space, helping to cool the polar regions and the planet overall. The polar regions support a high level of biodiversity, particularly in marine environments, making them some of the most important yet fragile ecosystems on Earth (27, 28). Both the Arctic and the Antarctic play crucial roles in carbon sequestration. In the Arctic, carbon is stored in the permafrost, tundra, and boreal forests (29), and in the Arctic Ocean and the Southern Ocean at least half of all carbon dioxide (CO_2) uptake by the world's oceans occurs (30–32). This makes the polar regions an important carbon sink but exposes their marine environments to greater acidification, threatening the viability of shelled organisms at the base of polar marine food webs (33, 34).

The polar regions are vital to the overturning circulation of the world's oceans, as they drive the sinking of cold, dense water, which is essential to global ocean currents (35, 36). Direct measurements in the deep Southern Ocean suggest that a ~30% slowdown in the Antarctic overturning has occurred over the past few decades in both the Weddell and Ross Seas, which has been linked to both meltwater and wind changes (37, 38). Model projections suggest that this slowdown will continue for at least the next few decades and that the southern limb of the ocean overturning circulation could collapse within this century (39). The associated freshening of the Southern Ocean is affecting ecosystem functions and loss.

Continuing the current trajectory of fossil fuel consumption and associated global warming is not viable considering the scale and magnitude of the consequences for the polar regions, and their severe regional and global implications (40); under current policies, an intermediate scenario points to an increase in global temperature from pre-industrial levels of approximately 3°C by 2100 (41). By contrast, rapid reductions in carbon emissions, reaching net zero emissions by mid-century, could stabilize global temperatures and curb polar changes, protecting the world and future generations from the worst effects of high emissions (42, 43).

Some scientists have proposed technological interventions in the climate, oceans, sea ice, or ice sheets as a potential complement to or alternative for reducing emissions (44, 45). Various terms are used to describe these approaches, with different framings resulting in different public perceptions (46). Some of these labels suggest a greater level of control than is possible, such as "climate engineering" and "emergent climate technologies". Other terms, such as "climate repair" and "climate restoration" give the misleading perception of being able to return to a previous climate state. The term "climate intervention" is sometimes preferred, drawing analogies to medicine. However, "intervention" suggests a precise and temporary measure, which does not accurately represent the reality of these approaches. In this article, we use "geoengineering", which encompasses a wider range of activities, such as the large-scale polar engineering ideas that are discussed here. We assess five prominent geoengineering concepts that aim to change heat uptake or distribution around the planet through various means: by increasing solar reflectivity within the atmosphere; diverting key ocean circulation patterns in the polar regions to reduce ice melting; increasing sea ice albedo or thickness; slowing the flow of ice sheets to restrict ice loss to the oceans; and enhancing CO_2 uptake by the oceans. We show that all five of these concepts are unlikely to be effective due to a range of factors: the scale and immediacy of the climate problem; harmful side effects within and far beyond the polar regions; failure to address key environmental protection concerns; greater governance and financing challenges than those that already exist in the context of the Paris Agreement; and the risk of distracting from urgent decarbonization efforts, thereby delaying and narrowing remaining and feasible carbon reduction pathways. Our assessment is focused on the polar regions, and is not exhaustive; therefore, it does not include CO_2 removal (CDR) technologies and practices, and/or nature-based solutions. Although the development of some CDR technologies, such as direct air capture, is still nascent, they will have to play a role in climate change mitigation (25).

Part 1: Polar regions' geoengineering assessments

We evaluate five prominent geoengineering concepts: (i) stratospheric aerosol injection (SAI); (ii) sea curtains (or sea walls); (iii) sea ice management (which involves modifying albedo and thickening sea ice); (iv) slowing ice sheet flow through basal water removal; and (v) ocean fertilization. Our evaluation is structured around the following six categories: scope of implementation, which spans both the Arctic and the Antarctic; effectiveness; feasibility; negative consequences; cost; and governance with respect to their deployment at scale (Supplementary Table 1). While these categories are consistent across all case studies, each proposal has unique technological, logistical, and ethical considerations that are discussed in detail in their respective sections.

Proposed concept 1: Stratospheric aerosol injection

Background

Solar radiation modification (SRM) refers to the intentional modification of the Earth's radiative budget to offset some of the effects of increasing greenhouse gases (GHGs)—but without reducing the gases themselves (25, 47). SAI is one of the proposed methods, which we discuss below (Figure 1); others include marine cloud brightening, surface albedo enhancement, cirrus cloud thinning, and space-based mirrors.

Budyko (48) published one of the first studies addressing climate change and the possibility of direct climate intervention via aerosol injections. Most of the historical research on aerosol injection stems from the study of the climate effects of major explosive volcanic eruptions. In 1991, Mount Pinatubo in the Philippines erupted, sending an eruption column 40 km into the atmosphere and creating a massive "cloud" in the middle-to-lower stratosphere. This event injected approximately 17 megatons of sulfur dioxide (SO_2) into the stratosphere. The resulting aerosol cloud quickly spread globally, achieving full coverage within a year. It significantly reduced the amount of net radiation reaching the Earth's surface, causing observable climate effects. Specifically, there was a surface cooling of up to 0.5°C–0.6°C in the Northern Hemisphere, equivalent to a reduction in net radiation of 4 W/m^2. Globally, temperatures cooled by approximately 0.5°C for nearly 2 years (49). The event demonstrated that the release of 15–20 megatons of SO_2 into the stratosphere could generate enough aerosols to counteract some global warming. More recent studies show that effective SAI would require lofting hundreds of thousands to millions of tons of material each year to altitudes of up to ~20 km to counter a substantial fraction of warming caused by GHG loading (25, 50, 51).

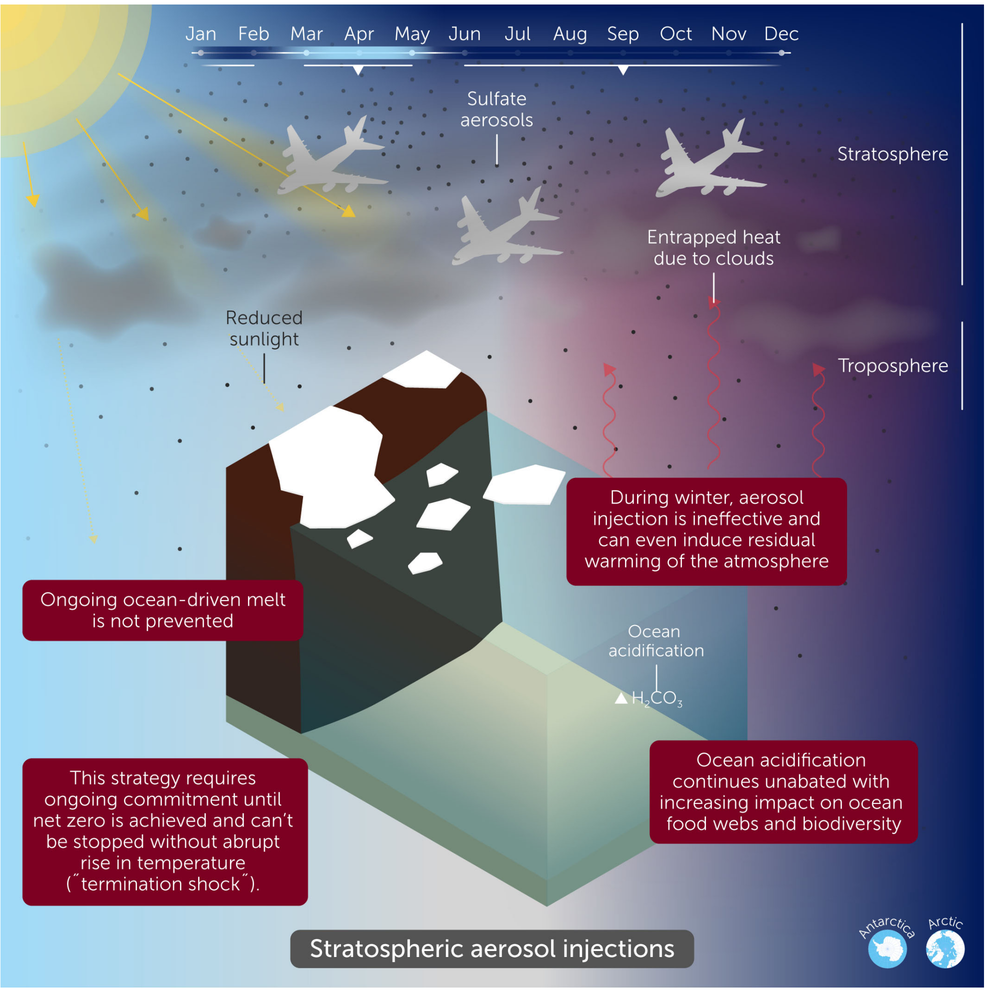

FIGURE 1
Stratospheric aerosol injection (SAI) in polar environments. SAI in polar regions will not be possible year-round, due to winter darkness, and may have unwanted and unintended consequences for regional climates, including those across territorial boundaries. The pale blue shading shows the effective time period for SAI in the Arctic. The Inset icons (bottom right) show whether the option has been proposed for Antarctica, the Arctic, or both.

Current research focuses primarily on the following types of aerosols:

(i) Sulfur dioxide (SO_2), which is converted to sulfuric acid aerosols in the stratosphere.

(ii) Sulfate aerosols, which are similar to those produced by volcanic eruptions. These effectively reflect sunlight and thus could reduce global temperatures but also pose risks, such as potential damage to the ozone layer and the creation of acid rain (52, 53).

(iii) Titanium dioxide (TiO_2), which is potentially less chemically reactive than SO_2, and thus may be less damaging to the ozone layer, but is still in the experimental stage (52).

(iv) Calcium carbonate ($CaCO_3$), which might neutralize some of the acidifying effects of other aerosols and reduce ozone depletion risks but is also still under investigation (52, 53).

Effectiveness and feasibility

In the absence of any field assessments and pilot studies, and based on a variety of modeling investigations, the Intergovernmental Panel on Climate Change (IPCC) (25) has noted large uncertainties in the effectiveness of solar geoengineering deployment (51), substantial knowledge gaps regarding its cost-effectiveness, and a range of risks associated with deployment. In the polar regions, the uncertainties are even higher due to seasonally reduced sunlight and aerosol lifetimes.

It has been suggested that aerosols could be injected into the stratosphere using balloons, airships, and/or artillery. However, the most efficient method would probably involve a fleet of custom-built and/or specially modified aircraft (54, 55). Smith and Wagner (50) estimate that 60,000 flights annually—0.15% of all current flights globally (56)—would be required for a lasting effect. Smith (57) recently highlighted the Boeing 777F as a potential candidate, although it would require substantial modifications, with a fleet of 90 planes focusing on deployment in the polar regions. Deployment strategies would include aerosol injection (i) in the tropics or subtropics (at or equatorward of 30°); (ii) uniformly across all latitudes; and (iii) in the sub-polar or polar regions (at or poleward of 60°). Typically, the tropopause is lowest in altitude in the polar regions, facilitating larger payloads and requiring fewer planes to achieve a given injection mass (54, 57).

SAI would require a highly specific deployment to have a significant impact in the polar regions (58, 59). The radiative forcing from stratospheric aerosols depends on the amount of local incoming solar radiation and top-of-atmosphere albedo. Polar regions are less responsive to aerosol injection during sunlit periods because of their lower insolation and the higher albedo produced by ice and snow (60–62). Furthermore, injections are completely ineffective during the winter months in the polar regions. The Brewer–Dobson circulation, which is characterized by rising air in the tropics and descending air in the mid and high latitudes, affects the distribution and lifetime of stratospheric aerosols. Therefore, aerosols injected at high latitudes have a shorter lifetime and more localized cooling effects owing to their rapid removal by the poleward movement and descent of air (63), which calls into question the effectiveness of SAI in the Arctic. The effectiveness of SAI in preventing ocean-driven glacier retreat and sea level rise is also likely to be limited (64).

"Termination shock" is the rapid and severe warming that could occur by the unmasking of ongoing GHG emissions if any future large-scale deployment of solar geoengineering were halted (65). The sudden cessation would remove the reflective aerosols from the stratosphere, causing the Earth's climate to adjust abruptly to the conditions dictated by GHG concentrations, resulting in a swift, significant rise in global temperatures. Climate models suggest that following SAI termination, global surface temperatures would increase within a decade or two to values consistent with GHG forcing. This introduces profound systemic uncertainty regarding the long-term viability of SAI and its potential to destabilize the global climate system further. Major water cycle changes would occur, including a rapid increase in global mean precipitation (66). Parker and Irvine (65) claim that timely policies could avert termination shock. However, relying on SAI without GHG removal would probably require prolonged (even permanent) injection, entailing continued financial, ecological and human costs.

The readiness of SAI for implementation varies greatly between polar-specific and global deployments (67, 68). If a launch decision were made by 2030, polar SAI could theoretically be operational regionally by 2040. On a global scale, however, if an international decision to proceed followed a breach of a temperature threshold of 2°C, the decision could be made around 2050 under continual warming from today, meaning that SAI would only be fully operational by 2060 (69). However, many obstacles stand in the way of what is theoretically possible, including financing, governance, and the determination of—and taking responsibility for—negative consequences. The lack of international governance frameworks to oversee SAI deployment compounds these uncertainties, making it even more challenging to predict the long-term impact of this geoengineering option. Overcoming these and other issues will take far longer than the implementation of available actions to strengthen GHG emission reductions and engage transformative adaptation.

Negative consequences

In the polar regions, atmospheric injections would be ineffective in winter owing to the lack of sunlight. Instead, they could lead to residual warming in winter (due to the blanketing effect of cloud cover), potentially altering the high-latitude seasonal cycle (70, 71), with potential consequences for the water cycle through atmospheric drying. Atmospheric injections could also cause stratospheric heating, which may alter atmospheric circulation patterns, leading to wintertime warming over northern Eurasia, among other unintended consequences (71).

SAI would not address the non-temperature-related effects of GHG emissions, such as ocean acidification. In fact, they could exacerbate acidification, especially if sulfates (the original source of "acid rain" emissions from coal-fired power plants) were used, with consequent negative impacts on ecosystems and economies. The Arctic and the Southern Ocean already show seasonally corrosive conditions for shelled organisms due to current atmospheric CO_2

levels, and shell damage from increasing acidification was observed from samples taken as early as the 2000s (72). Year-round corrosive conditions are projected to spread throughout much of the polar marine ecosystem with even moderate emissions pathways at CO_2 levels above 450 ppm (26). Ocean acidification is a problem with a very long time frame; it would take 30,000–50,000 years to return to 2012's pH levels (73). Acidification rates are already higher today than at any point in the last 300 million years (74). Exacerbated acidification raises the specter of extinction for many polar marine shelled animals and the economically important species that depend on them, such as krill and cod (34, 75).

Injections of sulfate aerosols can also lead to chemical reactions in the stratosphere that deplete ozone (76). Ozone depletion increases the amount of ultraviolet radiation reaching the Earth's surface, which has harmful effects on human health (see below), ecosystems, and biodiversity as a whole (77, 78).

Using SAI to differentially cool one polar region alone could disrupt global climate patterns. An imbalance in cooling between the hemispheres could shift the Intertropical Convergence Zone, potentially interfering with seasons (63, 79, 80) and reducing rainfall in some regions, thereby affecting water availability and agriculture (81).

Concerns exist regarding the effect of aerosol inhalation on human health. Sulfuric acid aerosols can irritate the respiratory system, causing coughing, airway irritation and inflammation and, in severe cases, respiratory distress. Chronic exposure has been associated with an increased risk of laryngeal cancer owing to long-term irritation and inflammation. This could lead to increased healthcare costs and add a burden on medical infrastructure, with particular risks for vulnerable populations (82).

Costs

SAI is frequently portrayed as a relatively inexpensive method of climate intervention.

However, Smith et al. (69), looking at a time horizon of 15 years in the future, estimated the direct costs at approximately US$13.5 billion for acquiring 90 Boeing 777 aircraft, US$3.2 billion for necessary infrastructure, and approximately US$1 billion annually for operations. If these expenses were distributed among 30 countries, each would contribute approximately US$55 million/year. Another recent article has suggested that the annual operating costs, which are larger than the capital costs estimated by Smith et al. (69), would likely grow significantly because of the increase in the amount of material that would be required for injection as GHG concentrations rise. Their study estimates that the injection rate would increase "by a factor of 34" between 2020 and 2080, under a scenario of global warming at Representative Concentration Pathway 4.5 (RCP4.5) (83), so the costs would grow sharply beyond 2040.

However, these calculations assume that the interventions will work as planned, only consider direct costs, and exclude indirect ones such as monitoring and measuring possible impacts, along with the costs of liability related to adverse impacts. Previous studies, such as the one by Smith (84), and more recently by Bronsther and Xu (85), indicate that the perception of SAI as a low-cost solution may be a misleading oversimplification of the financial realities. Furthermore, such estimates do not include potential unforeseen negative impacts on (i) weather systems, ecosystems, human health, and agriculture; (ii) the effectiveness of renewable energy technologies and the requirements of multi-century commitments (86–88); (iii) the immense potential costs associated with termination shock (see below); (iv) the mistrust and rivalry concerning geopolitical and economic interests among key states (89); and (v) the legal challenges in determining and assigning attribution and liability for such impacts, and the absence of insurance and/or whether insurance is even possible.

Governance

The absence of governance for SAI and the absence of deliberation spaces (90) are major challenges (46), with some scholars arguing that deployment may be largely ungovernable (91, 92). In the polar regions, SAI could even be used as a disruptive tool in a wider geopolitical context (89). Unilateral deployment of SAI by one country or a group of countries, but opposed by others, could make international cooperation on addressing climate change harder to achieve and lead to increased geopolitical tensions in general (93, 94). Although political disputes over geoengineering have already been shown to include much deeper issues (95), these tensions are usually ascribed to the fact that SAI has global effects that could vary between countries. While some regions might experience cooling and reduced climate risks, others might face adverse effects such as changes in precipitation patterns and agricultural productivity. This could exacerbate existing inequalities between developed and developing countries. No current international agreements explicitly prevent countries from using geoengineering strategies that could negatively impact other countries (96). In the current geopolitical environment, which is characterized by increasing tension and rivalry, SAI might also prove politically infeasible owing to countries distrusting the intentions of states advocating for research or deployment and may contribute to international tension if subject to disinformation campaigns (89).

No enforceable framework currently exists for international cooperation on SAI, despite some calls for an ethical framework and the recent development of suggested principles (46, 97–99). Efforts to introduce the topic at successive United Nations (UN) Environment Assemblies have failed due to widespread opposition among governments. In 2021, the Swedish Space Agency rejected serving as host for the Harvard-based Stratospheric Controlled Perturbation Experiment (SCoPEx) due to opposition from the Indigenous Arctic population, wider civil society and several Swedish universities; the same project had originally been proposed to take place over Navajo lands in the United States (100).

The European Union has stated that it "…does not consider SRM as a solution, as it does not address the root cause of the problem, which is the increase in greenhouse gases in the atmosphere" (101). In line with this position, the European Commission's Group of Chief Scientific Advisors recently recommended a Europe-wide moratorium on the deployment of

SRM technologies, citing significant risks and uncertainties (102–104). The report also states that "SRM funding should not divert funds and intellectual effort away from climate change mitigation or other related research activities" (102), reinforcing the need to prioritize proven emissions reduction strategies over speculative geoengineering interventions.

In January 2023, Mexico announced that it would ban solar geoengineering experiments following unauthorized tests conducted by the United States-based startup Make Sunsets (105), which released weather balloons containing SO_2 into the atmosphere without governmental authorization. Understanding the power relations and risks inherent in non-state funding of solar geoengineering is a further related challenge (106), particularly as there is a lack of transparency surrounding the funding of geoengineering projects (107).

In January 2022, 400 scientists proposed a non-use agreement on solar geoengineering with five core principles: no public funding, no outdoor experiments, no patents, no deployment, and no support in international institutions; the African Union and the European Parliament have called for support on this agreement (108). Establishing such an agreement should be feasible as there are many precedents in international law that could be used to impose an international ban on the development of solar geoengineering technology, including the Chemical Weapons Convention and the Treaty on the Prohibition of Nuclear Weapons (109).

Another significant concern is that the implementation of SAI would potentially distract and detract from necessary efforts to reduce GHGs (110).

The potential social disruptions would be substantial. There could be significant public resistance due to concerns about the potential side effects and the ethical considerations of deliberately altering the climate. Public protests and legal challenges could arise, complicating the implementation of these programs (111).

Proposed concept 2: Sea curtains/sea walls

Background

Wolovick and Moore (112) and Moore et al. (113) proposed installing artificial structures to prevent warm water masses from reaching the buttressing ice shelves and grounding zones of the Antarctic and Greenland ice sheets to reduce ocean warmth-induced ice-sheet melting and mass loss. The initial idea of building artificial sills up to 100 m high, or artificial pinning points up to 300 m high, on which an ice shelf could ground, has now been discarded. Now favored are "seabed curtains" (114, 115) comprising flexible buoyant structures anchored to the seabed at depths between 700 and 1,000 m (114), with 150–500 m high curtains (depending on location) extending upward as a series of thin, flexible overlapping panels (Figure 2).

Effectiveness and feasibility

The installation of such structures at depth and on various substrates is extremely challenging; this is compounded further by the harsh environment and the remoteness of the envisaged target areas, especially in the Amundsen Sea region of West Antarctica. The prefabricated foundations would have to be substantial to counteract the buoyancy forces of the curtain, and their necessary size may even exceed the capacity of ships to transport them (115). The proposed "outer" curtain route in the Amundsen Sea is on soft seafloor sediment. The potential for instability and mass movement due to "loading" on the seabed would need to be carefully assessed. In contrast, the "inner" curtain routes would require foundations built at least partly on rough bedrock channels, with steep slopes and the potential for strong currents scouring the topography (116–118). Shaping a prefabricated foundation structure to such a rough surface would be challenging even on land and even more so at depths of several hundred meters in Antarctic waters with icebergs and sea ice present, and especially with the need for precise installation of anchors in both hard and soft surfaces (115).

According to numerical modeling, such structures might successfully divert warm water from one ice shelf system, but their net efficacy may be compromised by the unintended rerouting of this water to other systems (119). Another modeling study concluded that reducing grounding line melt rates by up to 5 m/year below present levels could promote the re-advance of some ice streams (even after extensive prior retreat). However, reversing Antarctica's contribution to sea level rise also requires a substantially increased ice-surface accumulation (120). Feldmann et al. (121) estimate that at least 7 Gt of artificial snow would be required to balance the ice sheet around the Amundsen Sea, but this vast amount of ice would need to be applied over 10 years to be effective and, presumably, sustained at a high level thereafter. These studies call into question the usefulness and practicality of the approach.

Another challenge is that the deployment site is in one of the harshest and most remote environments on Earth, with a transit time of over 1 week from the nearest port and access likely to be possible only for a few months each year owing to polar darkness and extreme ice and weather conditions. Even today, the handful of ice-strengthened research ships that try to undertake short expeditions in this area are hampered by such conditions, often have to change work locations, and frequently fail to get to the region entirely due to impenetrable sea ice. Hazardous sea ice and iceberg collision risk have frequently thwarted attempts to reach the installation sites proposed by Keefer et al. (115) over the 40-year period in which this region has been targeted by ice-breaking vessels for academic research. A literature survey of cruise reports, and interviews with the principal investigators of research expeditions undertaken in the region, has revealed that 56% of cruises experienced at least partial disruption due to sea ice or had significant difficulty entering or exiting the area; 22% were unable to access the region altogether (122, 123). For example, the Inner Bay curtain site proposed for offshore Thwaites Glacier (115) has only been accessed once in the last 40 years despite frequent expeditions targeting the glacier front (117), while several

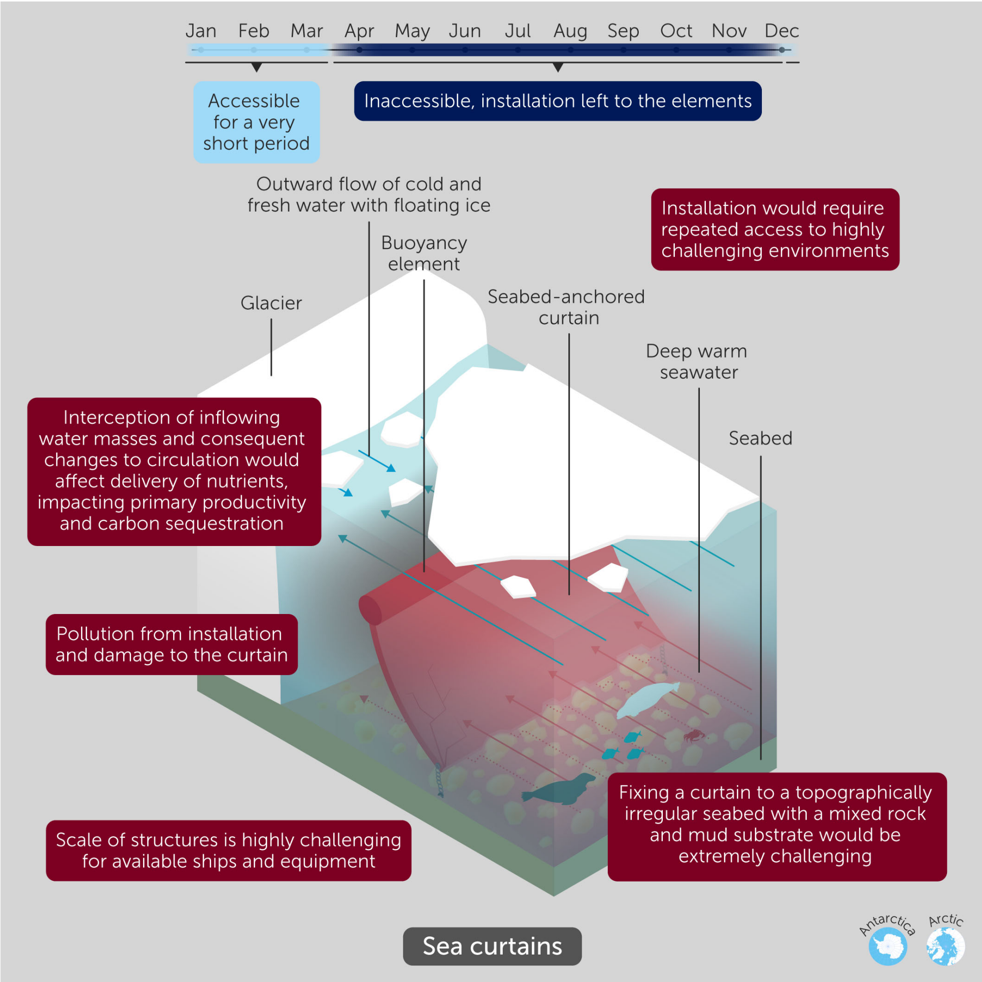

FIGURE 2
Sea curtains to block warm water from flowing towards ice sheet grounding zones. Installing structures spanning many tens of kilometers is a massive technological challenge that will require operations across some of the world's roughest seas and sustained work in ice-covered locations that even modern ice-strengthened vessels cannot always reach. These curtains will probably have unwanted consequences on ocean circulation and ecosystems. The pale blue bar shows the relatively short operational window for ships in the Amundsen Sea, Antarctica. The Inset icons (bottom right) show whether the option has been proposed for Antarctica, the Arctic, or both.

oceanographic moorings remain unrecovered in other parts of the Amundsen Sea continental shelf region despite multiple attempts to retrieve them in different years. Furthermore, even in years when sea ice conditions have been favorable, the risk of iceberg collisions has forced the abandonment of activities. This includes several locations where ships necessarily remain stationary for relatively short periods of time, such as for sediment drilling (124), and also the far greater task of installing complex foundations across rugged topography.

Keefer et al. (115) have argued that all installation vessels would need to be ice-class strengthened to Lloyd's A1 classification and capable of holding position. Currently, very few ships have this capability, with the majority of them committed to Northern Hemisphere operations; new ones would cost on the order of US$500 million each. These cost estimates are based only on sea curtains in the Amundsen Sea area, but there are other parts of the ice sheet margin that are potentially vulnerable and even more remote from logistical hubs, such as the Cook Ice Shelf, and the Mertz and Ninnis Glaciers in East Antarctica (125). Any installation elsewhere in Antarctica would be scaled in cost accordingly. Similar ideas have been proposed for Greenland, where artificial barriers could be built in glacial fjords to prevent warm deep waters from reaching marine-terminating glaciers (113). While building a berm in Greenland's fjords would be less logistically challenging than in Antarctica, the effectiveness of such interventions might be limited since the Greenland Ice Sheet is also highly susceptible to atmospheric-driven melting (126).

Negative consequences

The installation of sea curtain structures is likely to have far-reaching detrimental marine environmental consequences. These include potential effects on oceanic circulation, sea ice, and marine ecosystems from the interception of circulating water masses, the deflection of water masses elsewhere, and the impacts of any water masses that leak through barriers or "overtop" the uppermost elements (115).

The presence of barriers to water masses will also act as barriers to marine life, such as demersal fish, mobile benthic invertebrates, and the seabirds and marine mammals that feed at depth in these regions (127). Interception of inflowing water masses and the consequent changes in circulation and sea ice will affect the delivery of nutrients—most notably iron (128)—from upwelling and from ice melt in the region, with consequent impacts on primary productivity and carbon sequestration. Installation of towed floating structures, as suggested by Keefer et al. (115), may also introduce non-native species to the seabed and water column around Antarctica with unknown consequences for marine ecosystems (129, 130).

Other potential consequences include pollution from installation and damage to the curtains, additional emissions associated with transportation and installation, and the need for ongoing maintenance over decadal timescales (the planned lifetime of the curtains being 25 years). The material to be used for the curtains is not yet clear. There is the possibility that elements of the curtains, which are hundreds of meters long, could degrade and/or become dislodged over time, posing a severe threat to marine life and shipping.

Installing such a structure would entail considerable emissions. Transiting an icebreaker more than 2,500 km from the nearest major port while towing large floating structures through rough seas would be operationally risky and carbon-intensive. For example, the German research vessel Polarstern consumes approximately 900 tons of fuel/month (equivalent to 2,800 tons of CO_2) with a far higher consumption when breaking through sea ice. Towing large structures through sea ice is extremely difficult, and so the working season would probably be <3 months/year. Each transit for a single curtain section would probably take well over a month, with a likely maximum of four to five round trips per year being possible, each ship emitting 10,000–15,000 tons of CO_2.

The complexity of these logistical challenges amplifies systemic uncertainties about the long-term feasibility of sea curtains. Any structural failure due to an iceberg collision, strong currents, or foundational instability could compromise the entire intervention, negating potential benefits and leading to unforeseen environmental consequences. Such uncertainties, combined with high costs and engineering demands, underscore the speculative nature of this approach.

Costs

The costs of installing sea curtains will probably far exceed the maximum of US$80 billion for an 80 km structure, spread over a decade, as estimated by Keefer et al. (115). Their cost estimate of US$1 billion/km can be compared with the real-world cost of the Thames Barrier, a 500 m long structure across the River Thames in London, United Kingdom. This was built on the surface in water <10 m deep immediately adjacent to an enormous logistics hub (i.e., with no shipping required). Nevertheless, it took 8 years to build and cost £535 million in 1982 (131), equivalent to £2.4 billion (US$3.1 billion or US$6.2 billion/km) at 2024 prices. The Three Gorges Dam in China, which is approximately 2 km wide and 180 m high, cost ~US$37 billion in 2008 (132), equivalent to US$54 billion in 2024; approximately 25 times more per kilometer than presently reported for the Amundsen Sea curtain.

Governance

Governance of sea curtains in Antarctica would fall under the Antarctic Treaty System. Article 8 of the Protocol on Environmental Protection requires a Comprehensive Environmental Evaluation (CEE) for any activity with more than a "minor or transitory" impact (133). The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) may also have concerns regarding the potential consequences for the marine ecosystem. The installation of a sea curtain would be orders of magnitude larger than any construction activity seen previously in Antarctica and would require not only an estimation of all likely impacts but also a rigorous associated program of impact monitoring and mitigation. Obtaining international consensus to intervene in Antarctic processes on such a large scale has never been attempted before, and those advocating for the use of sea curtains have given this necessary requirement scant consideration thus far. Flamm and Shibata (134) have pointed to significant potential problems for such an idea within the Antarctic Treaty System (see Part 3), suggesting that—even if sea curtains could work without negative impacts—they may precipitate political fragmentation and "pose a risk of 'international discord'" in Antarctica, through concerns over "authority, sovereignty, and security".

Proposed concept 3: Sea ice management—modifying albedo and thickening sea ice

Sea ice albedo

Background

Sea ice cools the Earth by reflecting solar energy. Loss of sea ice in recent years has made the Earth's surface less reflective: according to a recent global study, sea ice has lost 13–15% of its radiative cooling effect since the 1980s, leading to increased solar heating (135). Scattering hollow glass beads over first-year Arctic sea ice could increase its albedo, promoting its survival into a second winter and beyond to re-establish multi-year ice (136).

Negative consequences and feasibility

The use of glass beads raises significant concerns that must urgently be addressed (Figure 3). First, there is the risk of ecotoxicity. Ecotoxicological testing is underway in vertebrates (136), but the impact on invertebrates appears to be unknown. Potential effects on zooplankton feeding behavior are of particular concern, given the size and nature of the beads. Second, the glass beads are metastable and will readily dissolve in the undersaturated seawater (137), potentially reducing their efficacy. Any means used to reduce the solubility of the beads will increase ecotoxicological concerns. The biogeochemical impact of bead dissolution in the low-silicon waters of the Arctic surface ocean, where diatom growth is seasonally silicon-limited (138–140), is unknown. Webster and Warren (141) have shown that massive quantities of glass beads would be required—approximately 360 megatons annually, an amount equivalent to the annual global production of plastic—which poses significant logistical challenges and substantial emissions during production. This scale introduces systemic uncertainties related to supply chains, logistics, and emissions associated with manufacturing, further undermining the feasibility of this approach. Finally, Webster and Warren found that microspheres actually have a net warming effect on Arctic sea ice. They can absorb a significant portion of solar radiation, darkening surfaces with high albedo and accelerating sea ice loss rather than preserving it.

The Arctic Ice Project, which aimed to use this glass bead technology to slow ice melt, was recently shut down after ecotoxicological tests revealed potential risks to the Arctic food web (https://www.arcticiceproject.org/a-final-chapter/). This underscores the uncertainties and risks of geoengineering interventions in fragile ecosystems.

Costs

Beyond the environmental risks, the financial feasibility of deploying glass beads at scale is debatable. In addition to the costs of materials, manufacturing, and logistical operations,

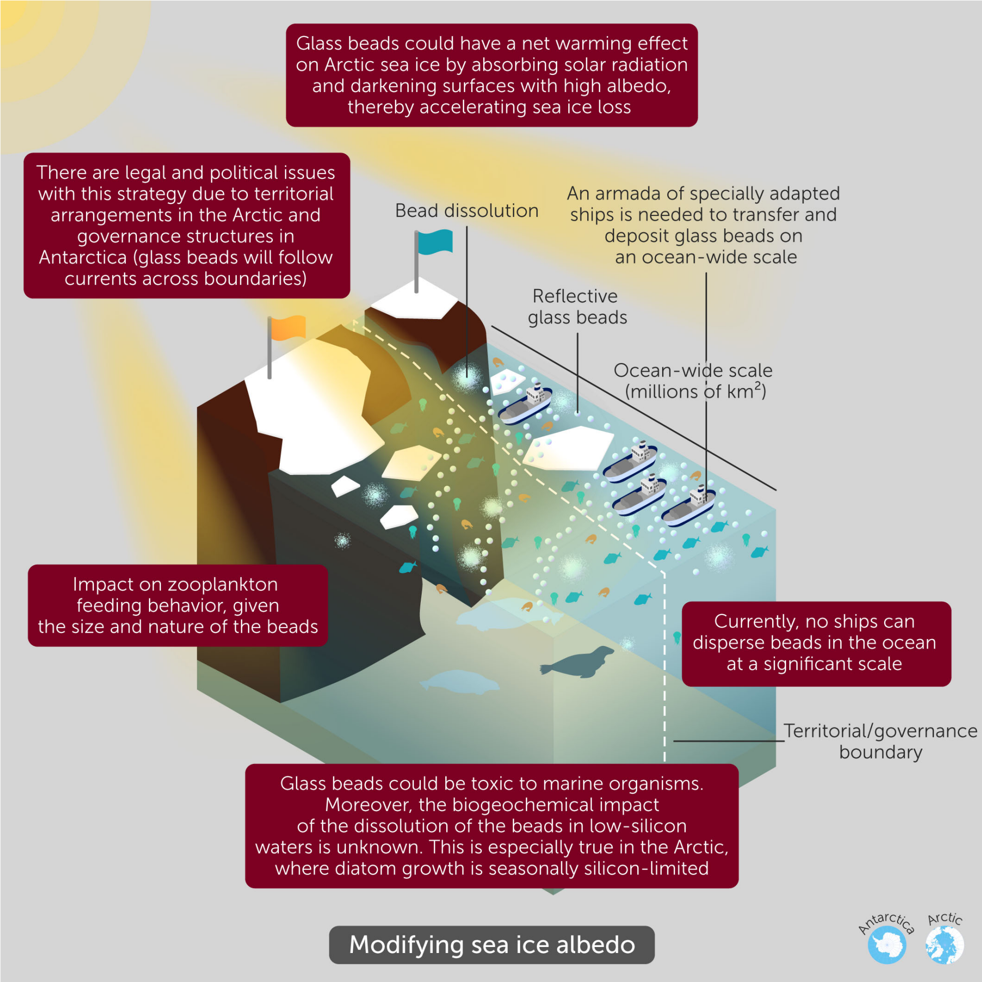

FIGURE 3
Using glass beads as a means to reflect sunlight off polar surfaces. Changing albedo by adding particles to the ocean may actually decrease albedo, would require deliberate pollution of ecosystems, and may cross governance boundaries. It is also unlikely to be logistically possible to operate at the scale necessary to make a significant difference. The inset icons (bottom right) show whether the option has been proposed for Antarctica, the Arctic, or both.

research and regulatory approvals would add further expenses, making this approach economically unviable compared to direct GHG mitigation and adaptation strategies.

Governance

The use of glass beads also presents important governance challenges. Ocean currents and surface winds carry sea ice across sovereign boundaries in the Arctic Ocean and would do the same for glass beads in surface waters. The international legality of a single nation introducing an environmental disturbance into another would be a serious issue requiring resolution before any deployment. No such agreements exist at present, effectively blocking the roll-out of this technology. Another essential governance factor concerns Indigenous Arctic communities, and their preparedness for and support of these interventions that will affect the natural systems that support their livelihoods and culture (142).

Arctic sea ice freezing

Background

There is much debate concerning whether Arctic sea ice can be artificially "thickened" to counteract sea ice loss (Figure 4). It has been suggested that sea ice can be thickened by pumping seawater either onto the ice surface, where it will freeze, or into the air, where it will fall as snow onto the ice (143–145). Desch et al. (144) suggest that winter sea ice could be thickened by ~1 m using wind-powered pumps that spray seawater onto the ice surface. They propose that deployment of these pumps across 10% of the Arctic Ocean could "more than reverse current trends of ice loss in the Arctic, using existing industrial capacity".

Effectiveness and feasibility

For the technique to be effective on a local scale, Pauling and Bitz (145) suggest that it would have to be deployed "almost

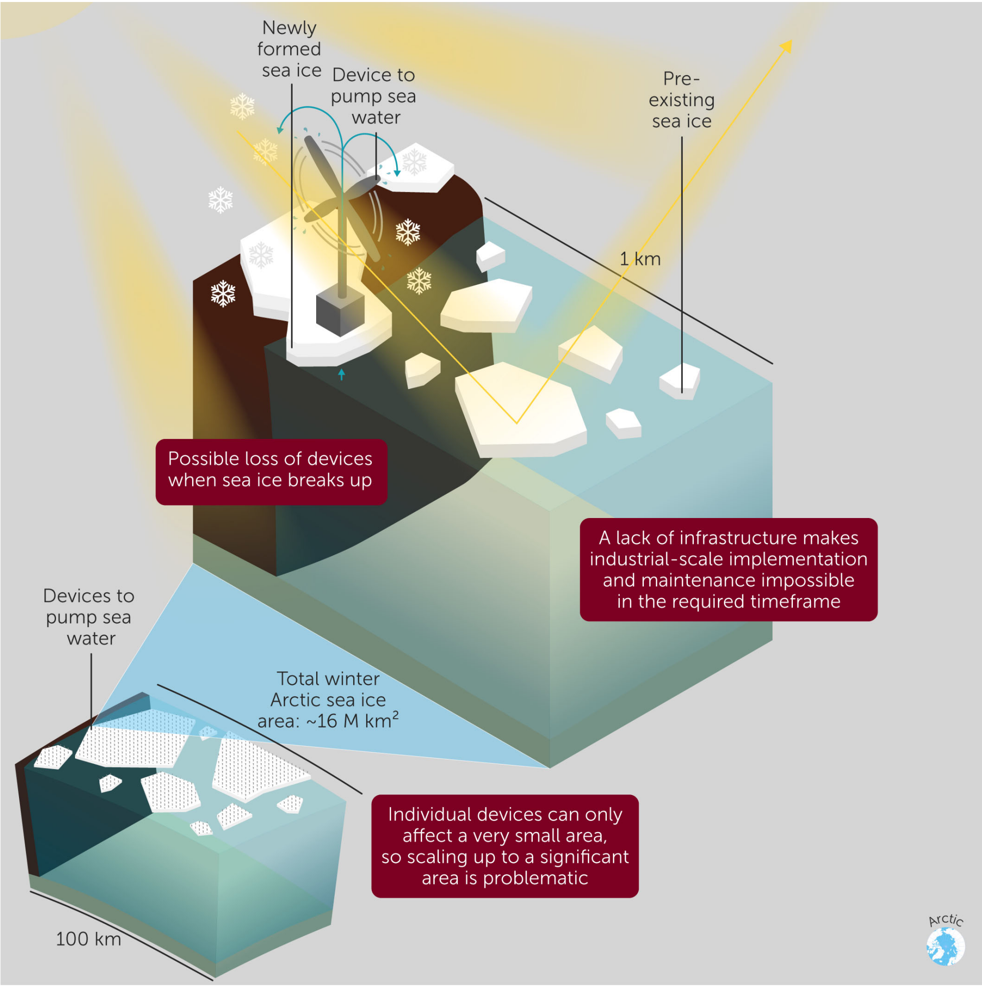

FIGURE 4
Arctic sea-ice thickening to counteract the loss of ice. Techniques to thicken sea ice would require a very large number of individual devices to be deployed onto the winter sea ice, and it is unlikely to be logistically possible to operate at the scale necessary to make a significant difference. The inset icons (bottom right) show whether the option has been proposed for Antarctica, the Arctic, or both.

immediately". It would not be possible to deploy these pumps at scale within this strict time frame. There are also challenges related to the scale of the deployment area; the long-term average Arctic sea ice extent varies between summer and winter from 5 to 16 million km^2. According to Desch et al. (144), 10 million pumps would be needed to cover 10% of the Arctic Ocean, and 100 million to cover the entire Arctic. To cover 10% of the Arctic within 10 years, they anticipate that one million pumps would need to be deployed each year, and they concede that this is unlikely to be logistically or financially possible (144). Therefore, sea-ice thickening is simply not feasible for use at a scale and at a rate that would be meaningful for sea ice protection. Furthermore, the scale of implementation of this method would require an unprecedented level of human presence in the High Arctic for initial construction and subsequent maintenance. Other inherent challenges may render the idea infeasible even at a local scale, such as the difficulty of keeping the pumps in place (considering the strong drift of sea ice), the need for year-round maintenance over such a large area, the sinking of the pumps if sea ice melts or breaks up, and governance issues—especially considering that the Arctic Ocean is becoming an increasingly congested space.

In addition to these challenges, it is also unlikely that this approach would be effective as a tool to mitigate global warming. A modeling study by Zampieri and Goessling (146) found that if seawater pumps worked, it could be possible to maintain late-summer sea ice cover at its current extent for the next ~60 years, but maintaining the ice would have a negligible effect on global warming. This contradicts the claim that restoring Arctic sea ice could be a tool to limit global warming (136).

Costs

Desch et al. (144) estimated production and transport costs of US$50 billion per year for 10% of the Arctic or US$500 billion per year for the entire Arctic. Although US$500 billion only represents ~0.5% of global GDP (~$100 trillion), it is still an extremely large financial investment for a technology that may not preserve the sea ice and, even if it did, would do little to mitigate strong global warming. Additionally, the long-term financial commitment required for pump maintenance and replacement due to wear and environmental damage adds another layer of uncertainty to the cost-effectiveness of this approach. Redirecting this investment to reduce GHG emissions would provide better value.

Governance

Any large-scale intervention affecting natural systems in the Arctic must be undertaken with an appreciation of the applicable sovereign and international governance structures (see Part 3). As with the "glass beads" idea, the flow of sea ice across sovereign boundaries means that issues may well arise between nations that agree to the installation of ice-thickening machinery and those that do not, especially for maintenance and removal purposes. In addition, the lack of an international framework to regulate such interventions creates the risk of unilateral action, which could lead to political tensions and disputes over environmental damage. Indigenous Arctic communities must also be included in governance discussions, as these interventions directly impact the natural systems they depend on for food and cultural practices (142).

Proposed concept 4: Slowing ice sheet flow through basal water removal

Background

The rate at which ice is discharged from ice sheets to the ocean is determined by the flow of outlet glaciers and ice streams toward their margins. Increases in flow rates, if not balanced by increased accumulation, contribute to global mean sea level rise. While mountain glaciers dominated the cryospheric contribution to sea level rise over most of the 20th century, ice sheet contributions have risen rapidly since the 1990s, and the combined contribution of both Greenland and Antarctica now exceeds that of mountain glaciers, adding 11.9 mm to global mean sea level between 2006 and 2018 (147). These trends are expected to continue, with the IPCC's Sixth Assessment Report being unable to rule out low-confidence projections that exceed 15 m of sea level rise by 2300 under a high-emissions scenario (147). It follows, therefore, that reducing the rapid flow of outlet glaciers and ice streams in Greenland and Antarctica could, in principle, mitigate future sea-level rise, especially mass losses from Antarctica, which experiences much less surface melting than Greenland. Building on this logic, some researchers (113, 148) have proposed geoengineering strategies aimed at increasing basal friction to ultimately slow down glacier flow, with a particular focus on removing the lubrication provided by the pressurized subglacial drainage system (113). Here, we present our logic for why we believe that these intervention strategies are scientifically flawed and likely to be logistically impossible.

Ice streams and outlet glaciers exist on a spectrum from those that flow through deep troughs to those that flow over relatively flat beds (149, 150). The former ("topographic ice streams") are common in both Greenland and Antarctica, and the latter ("pure ice streams") are exemplified by those that drain the Siple Coast of West Antarctica but do not occur in Greenland. The limited geoengineering case studies are from the Siple Coast ice streams (148), probably because they dominated much of the earlier literature on ice stream flow mechanisms (150); however, they are not a major contributor to recent sea level rise from Antarctica. Worryingly, the glacier experiencing the most ice loss, Thwaites Glacier, appears to be unconstrained by basal topography, and its deglaciation would probably impact the entire West Antarctic Ice Sheet (151, 152). Irrespective of their topographic setting, the rapid movement of ice streams and outlet glaciers is predominantly enabled by *basal sliding*—ice slipping along the bed—a phenomenon resulting from a combination of sliding at the ice-bed interface, and deformation of the bed itself (150, 153). The fastest-flowing ice streams are generally found in regions where water is routed down topographic troughs or accumulates at the base, acting as a lubricant and reducing the effective pressure of the overlying ice (150). Increased water pressure in these areas is directly linked to increased glacier velocity, resulting in accelerated ice discharge (154).

In Antarctica, subglacial water is generated at the bed primarily by the melting of basal ice due to a combination of frictional heating, geothermal heating, and pressure melting (155). Unlike in Greenland, supraglacial meltwater does not reach the bed in appreciable quantities. It may also originate from Antarctic groundwater; a relatively recent focus of research, which could account for as much as half of the water beneath ice streams (156, 157). While groundwater has been identified at the margins of ice sheets (158), there is currently only limited evidence of groundwater systems beneath Antarctic ice streams (159). However, as there are huge sedimentary basins present beneath the ice (160), it is very probable that water from these basins plays a major role in modulating ice flow (161), especially on decadal timescales (162). Hence, any study looking to extract basal water to reduce water pressure must account for fundamental uncertainties in the role of groundwater.

The rates of basal meltwater production are generally low (mm/year), but over large areas of the ice sheet bed this leads to large volumes of subglacial water available to and transported beneath ice streams (155, 163). Furthermore, the subglacial water system is interconnected and continuously replenished, comprising a network of subglacial streams and lakes (164, 165). In contrast, Greenland's subglacial water is mostly generated at the surface and then delivered to the bed via moulins, providing a direct link between subglacial water and climate change. Importantly, in Antarctica there is no widespread link between basal melting and the atmosphere. However, Kazmierczak et al. (166) demonstrate that the long-term Antarctic response to climate forcing will be modulated to a degree through the flow of basal water.

Geoengineering strategies to reduce ice flow and glacier sliding fall into three main categories (148):

(i) **Drilling/drying:** This involves drilling to the subglacial bed and reducing water pressure there by pumping subglacial water to the ice surface. The objective is to increase basal drag by reducing water pressure, thereby slowing glacier flow.

(ii) **Cooling:** These approaches aim to reduce glacier flow rates by promoting heat flow from the bed to the surface or by introducing coolants into the bed.

(iii) **Obstructing:** This involves constructing obstacles (such as artificial rock outcrops) at the bed to increase basal friction and reduce the dependence of friction on water pressure, thereby impeding glacier flow (167).

Effectiveness and feasibility

Here, we focus on the scientific and logistical challenges of drilling/drying, but many of these apply equally to cooling and obstructing (Figure 5). We anticipate the effectiveness of drilling/drying to be limited, owing to the highly dynamic spatial and temporal nature of subglacial drainage.

The location, timing, and sphere of influence of each drill hole would be critical. In Antarctica subglacial water production is spatially extensive, but most basal water flows in discrete channels (155) that form intricately branched subglacial hydrologic systems. Therefore, multiple drill holes would be required, each syphoning a different branch—assuming these could be accurately located from surface geophysical surveys. This also assumes that the subglacial drainage system is stable; however, a wealth of evidence shows it to be highly variable, both spatially and temporally (168–170). Furthermore, once the ice stream bed is accessed by a drill, basal sliding will quickly move the drill hole base downstream. Therefore, even if a channel or subglacial lake is connected to the surface by the drill hole, the ice flow above it would act to break the connection within days to weeks. As for groundwater, we presently have no means to consider its extraction.

In Greenland, surface water could be removed or rerouted to prevent it from reaching the bed, but the transient nature of the supraglacial system (169, 171) would necessitate adaptable camps, machinery, and logistics. Maintaining infrastructure on a melting ice surface is a significant challenge requiring almost constant maintenance. Water would have to be removed from the ice sheet and routed elsewhere without it reaching the bed via downstream moulins or crevasses. Additionally, this would have no impact on meltwater generated by frictional heating at the bed of large topographic ice streams (172). Furthermore, channeling large volumes of supraglacial water to the bed would lead to low-pressure channelized drainage systems that would act to reduce annual ice flow velocities, rather than increase them (173). Greenland's subglacial hydrology evolves seasonally; toward the end of the melt season, high volumes of subglacial water evolve into efficient channelized drainage systems that lubricate less of the basal area, thereby decelerating the ice flow (174). Therefore, we consider it highly unlikely that basal water extraction in Greenland, either directly or through supraglacial diversion, is a feasible means to decelerate ice flow, and it may even have the reverse effect.

In Antarctica, targeting the trunk of the ice stream for water removal is unlikely to work as it is the cumulative velocity of the entire ice stream that needs to be reduced. Removing water from upstream and/or in the onset zone of ice streams would be the most effective way to reduce the overall water supply. However, the inland plateau is the most difficult place to access and has the thickest ice, making drilling even more challenging. Moreover, boreholes would have to be kept constantly open because subglacial water production is continuous. Draining the bed in the onset zone or upstream portion of an ice stream would theoretically steepen the ice surface slope and thereby increase driving stresses and pressure melting at the bed, much in the same way that glacier surging is triggered. Indeed, even if drainage slowed ice flow in a particular area, the ice sheet/stream would thicken upstream, and the resulting changes in the ice surface slope would displace basal water into neighboring regions, potentially accelerating flow elsewhere (175). This 'water piracy' mechanism has been attributed to the shutdown of the Kamb Ice Stream (formerly Ice Stream C) (176), which will probably oscillate

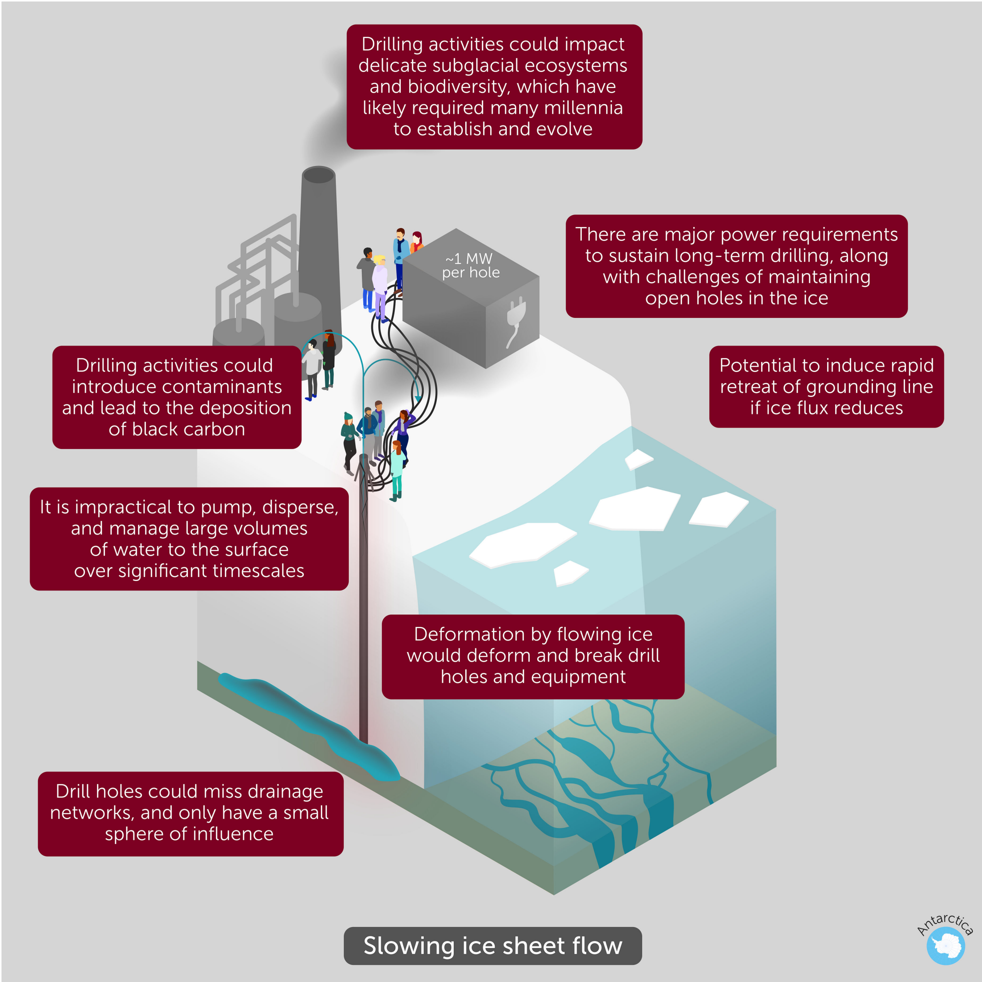

FIGURE 5
Subglacial water removal in ice sheets to slow ice flow to the ocean. Drilling to the bed of thick, flowing ice is highly technologically challenging and has never been undertaken for the sustained period required to maintain the drainage of subglacial water. Subglacial drainage networks are currently pristine and not well mapped, so the introduction of drill holes into the network will probably be highly challenging to achieve reliably and could cause contamination both below and above the ice. The inset icons (bottom right) show whether the option has been proposed for Antarctica, the Arctic, or both.

between periods of fast and slow flow and could be reactivated this century (177).

Both observations and modeling show that the Siple Coast ice streams exhibit significant short-term variability owing to the complex interplay between adjacent ice streams (178). Hence, even if it were theoretically possible to slow down a portion of an ice stream, the resulting thickening would probably reactivate the ice stream, or neighboring ice streams would capture ice and/or meltwater (179). This type of "flow-switching" is preserved in the geological record of paleo-ice stream activity (180–184). This "self-organized" behavior is replicated in numerical ice sheet models (185–187) and during deglaciation of paleo-ice sheets (184). This means that, even if it were possible to slow the flow of one ice stream, there would probably be knock-on effects elsewhere, with other ice streams increasing in flow or reactivating to remove the excess mass.

The rapid flow of major outlet glaciers and ice streams could also be triggered by conditions at the terminus (e.g., major calving events, ice shelf thinning, or grounding line retreat along retrograde bed slopes), which would then propagate inland through increased flow velocity and dynamic thinning (188–190). Hence, even if upstream adjustments to water pressure and flow were successful, continued ice loss at the terminus could lead to modifications to glaciological change at borehole sites, rendering the sites suboptimal. A reduced flux of ice into the grounding zone could even lead to rapid glacier retreat if mass losses at the front (from iceberg calving and submarine melt) do not change. A system that is already close to instability could be "pushed over the edge" if the ice supply were insufficient to keep the grounding zone stable. For example, the grounding zone of the Institute Ice Stream in West Antarctica sits atop a major reverse bed slope that is kept stable by a delicate balance between basal melt rates, ice accumulation and ice flow (191).

Logistically, drilling for subglacial water presents significant challenges and potential consequences. First, drilling to the base of an ice sheet is a monumental undertaking, necessitating advanced equipment and expertise (192). To be most effective, this technique would require numerous drill holes scattered across the ice sheet, a logistical feat unprecedented in polar fieldwork. The sheer size of an ice sheet means that the endeavor is virtually impossible to execute.

Water under pressure deep beneath the ice surface will not naturally escape in significant volumes: the puncture of Lake Vostok in 2012 created a colossal hydrological shock that bent the drill head and caused massive hydrofractures in the ice base (193). However, only 5 m^3 of drilling fluid escaped to the surface because the water froze in the borehole. The Lake Ellsworth experience in 2012 also points to major challenges in drilling deep holes with water once, let alone repeatedly, and even if successful they will freeze after 24 h unless frequently reamed—requiring substantially more hot surface water (192). Borehole pumping would have to be sustained over long timescales, as the continuously produced basal water would need to be extracted throughout the year, including in winter. Again, because the ice in the interior of Antarctica is extremely cold, the boreholes would freeze rapidly (within hours) without continuous heating. Above the water level, the borehole would close under the pressure of the overburden and require regular reopening or casing. This issue becomes non-linearly more difficult as the water level drops.

Pumping water out from the subglacial system would be a significant task requiring considerable energy resources. Existing hot water drills use pumps that recover water from depths of about 100 m. This corresponds to the water level at overburden pressure in a 1,000 m deep borehole. If lowering the water pressure were successful, then the water would have to be pumped against an ever-increasing hydraulic head. Depending on how much water level lowering is needed (which is currently completely unknown), this would dramatically increase the energy requirements and might even exceed the capacity of existing downhole pump technology. Entirely new approaches, such as those used in oil extraction, may be needed. These approaches would require casing of the holes but, in active areas of the ice, significant borehole deformation would make casings vulnerable. Furthermore, successful drying would cause higher basal stresses, which would increase shearing and affect borehole operations.

A cursory power calculation estimates the power requirements to be in the multiple MW range (as exemplified by various deep-drilling projects in Antarctica, e.g., ANDRILL, SWAIS 2C, Subglacial Lake Ellsworth, and IceCube). This is a colossal level of power to accomplish in a remote location, and operating year-round in extreme cold and windy conditions is far beyond the capabilities of existing technologies. Providing such power requirements using nuclear power, for example, would be highly controversial in the context of the Antarctic Treaty. Solar farms at that scale are not realistic given the long polar winter and the formidable challenge of wind drifts. Wind turbines could theoretically work, but existing structures on moving ice are several orders of magnitude smaller than would be necessary.

At present, kerosene is commonly used for power in remote field locations, which poses another environmental risk: the deposition of black carbon on the ice surface. At the scale required for widespread intervention, such deposition would probably be counterproductive, exacerbating rather than mitigating the challenges posed by rapid glacier flow. Additionally, it takes approximately 12 barrels of kerosene to transport 1 barrel of fuel to central Antarctica. Another significant challenge is the management of pumped-out water on the surface. A proposed solution is to turn this into snow, using snowmaking equipment commonly used in ski areas. This is feasible in principle but would produce a large amount of snow and entail additional energy requirements. The necessary management of this snow would require automated procedures to move it away from the snow cannons. The maintenance of surface infrastructure in extreme cold and wind, drifting snow, and riming (freezing water on solar-heated surfaces) is also a serious impediment. For example, equipment commonly gets "drifted in" in the Thwaites area, where there is relatively high snow accumulation and wind drift (194). Both the pumping infrastructure and snow-making equipment would require protection from snow drifting.

Many of these challenges require entirely new engineering approaches that would take many years, if not decades, to develop, even with unlimited resources. We emphasize that although they are not considered in detail here, the proposed cooling and obstructing approaches will face similar challenges to drilling/drying, both scientifically and logistically.

Negative consequences

Despite the scientific flaws of attempting to slow an ice stream, drilling activities could introduce contaminants into pristine subglacial environments, damaging delicate, biodiverse ecosystems that have evolved probably over many millennia. These consequences underscore the importance of thorough risk assessment that considers all environmental impacts. The Scientific Committee on Antarctic Research (SCAR) has agreed to a code of conduct for Antarctic subglacial access (195), endorsed in 2017 by the Antarctic Treaty Consultative Parties (ATCPs). The Antarctic Treaty's Committee for Environmental Protection (CEP) has assessed deep-drilling access to the ice-sheet bed, and following its advice, authorization by ATCPs is only likely to be granted if procedures with proven effectiveness are used to sterilize the drilling water (196). Hot-water drilling with pasteurized water might be possible, but such work is technically challenging (192) and increases energy consumption. The use of ice cores, which use an antifreeze drilling fluid, would probably be incompatible with environmental protection. Drilling could also lead to the unintended alteration of ice structures and crevasse formation (197).

Costs

The Subglacial Lake Ellsworth program, which in 2012 unsuccessfully aimed to create a 3-km deep borehole for just 24 hours, cost approximately US$13 million (equivalent to US$18 million in 2024) (196). The proposed method of water removal would require multiple holes (tens to hundreds), and a continuous connection to the seabed (i.e., 365 days/year for years to come), adding orders of magnitude to the Lake Ellsworth figure, in addition to maintenance and monitoring. It is difficult to imagine such a large undertaking being possible without the establishment of a new coastal station in the vicinity, to which materials could be delivered by sea. This would serve as a year-round base for operations. The construction of IceCube would not have been possible without the existence of McMurdo, Antarctica's largest base, and the Amundsen–Scott station at the South Pole. Planning, approval, and construction of these types of bases is a decades-long undertaking.

Governance

As in the case of sea curtains (proposed concept 2), the implementation of this activity in Antarctica would fall under the Antarctic Treaty System. Article 8 of the Protocol on Environmental Protection requires a CEE for any activity with more than a "minor or transitory" impact (133). Given the high level of uncertainty surrounding both the effectiveness and environmental risks of basal water removal, it is unlikely that such an intervention would meet the Treaty's strict environmental protection standards. This activity would require not only an estimation of all likely impacts but also a rigorous associated program of monitoring and mitigation of impacts. This governance barrier further highlights the systemic obstacles to implementing this geoengineering concept.

Proposed concept 5: Ocean fertilization

Background

Ocean fertilization is a form of geoengineering wherein nutrients whose availability limits phytoplankton growth (e.g., iron) are added to the ocean surface water to promote photosynthesis and stimulate blooms, thereby increasing the biological drawdown of CO_2 from the atmosphere (198) (Figure 6). This enhanced fixation of carbon in surface waters is then expected to sink as particulate organic carbon (POC) to the deep ocean for long-term sequestration. This vertical advection is known as the "biological carbon pump" (BCP), in which a variety of biota from bacteria to zooplankton and fish control the magnitude and efficiency of carbon export to the deep ocean (199).

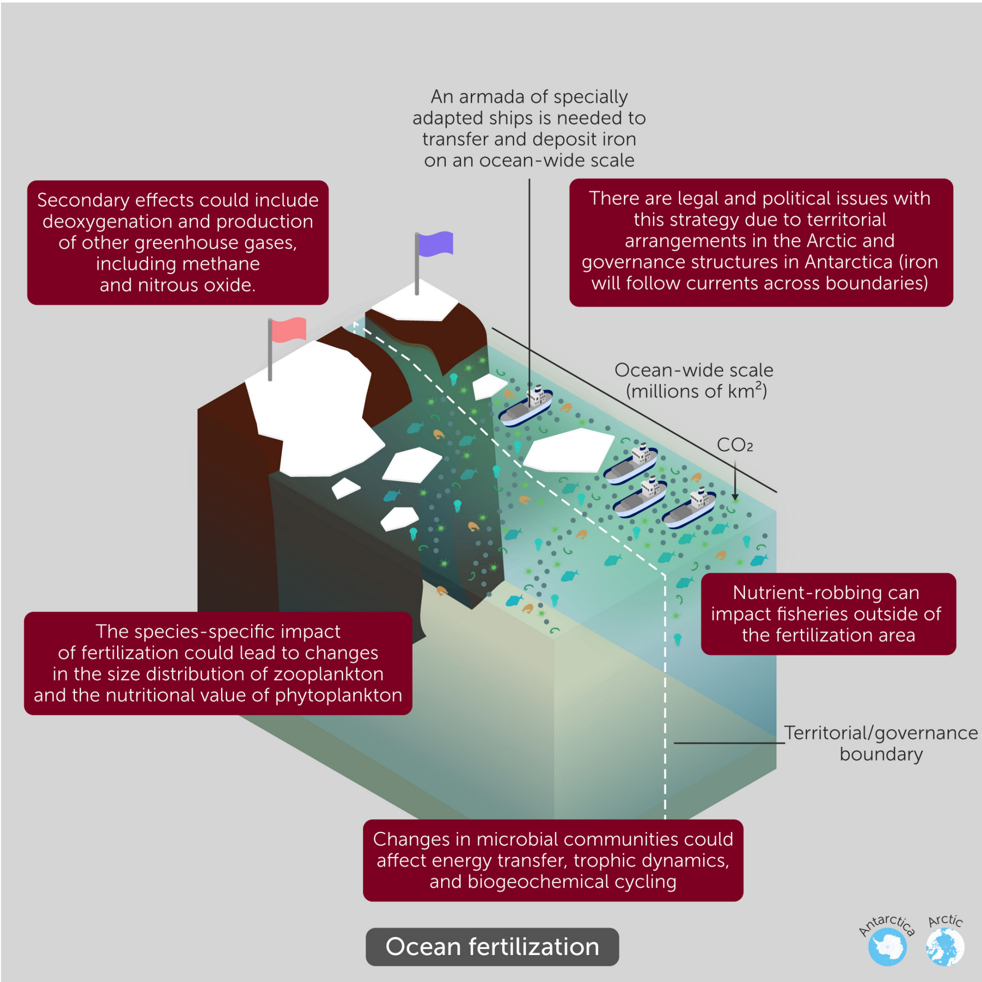

FIGURE 6
Ocean fertilization to "draw down" atmospheric CO_2. Negative impacts will likely include changes to food web structure, and fertilization could affect nutrients and fisheries elsewhere, including across territorial or governance boundaries. The inset icons (bottom right) show whether the option has been proposed for Antarctica, the Arctic, or both.

Prime areas for ocean fertilization are regions with high nutrient and low chlorophyll (HNLC) concentrations, specifically where macronutrients (e.g., nitrogen, phosphorus, and dissolved silicon) are abundant, but phytoplankton growth is restricted by other factors, such as a lack of micronutrients (e.g., iron). The Southern Ocean, an HNLC environment where productivity is limited by low iron availability, is considered an ideal location for ocean iron fertilization (OIF) (199–201).

Effectiveness and feasibility

From 1993 to 2011, 19 *in situ* OIF experiments tested the "iron hypothesis": twelve in the Southern Ocean, three in the Equatorial Pacific Ocean, one in the tropical Atlantic Ocean, and three in the Subarctic (North Pacific Ocean) (202). The results were inconclusive regarding the ability of OIF to increase the vertical export of POC to the deep ocean (203–205). In the Southern Ocean, OIF enhanced photosynthesis; however, an increase in carbon export to depth was documented in only one experiment (202). Export was monitored for only 2 to 6 weeks following iron addition, so it is not known whether longer-term observations would yield more positive results (202, 206, 207).

In terms of feasibility, full-scale deployment would require considerable effort and resources (see later)—involving an armada of ships designed to transfer and deposit iron at considerable ocean-wide scale. The means for the creation and supply of suitable material, and docks to support its loading, would also need to be established. None of this is available at present, making the concept's feasibility questionable.

Negative consequences

Scientists have expressed various concerns about the impacts of OIF on marine communities and ecosystems. While the addition of a limiting nutrient such as iron could enhance phytoplankton growth, there is no control over which species or groups of phytoplankton would be stimulated (205). This introduces significant direct uncertainty about the potential changes in phytoplankton species composition. Phytoplankton communities are typically a diverse mix of taxa. In the Southern Ocean, hundreds of species continually shift in terms of their standing stock and relative abundance. The groups and species that predominate can vary greatly in space and time, and diatoms, dinoflagellates, chrysophytes, and other groups can all be present simultaneously. Natural changes in light, temperature, macro- and micronutrients, and grazing pressure act synergistically to control species succession patterns. The species-specific impact of OIF within this mix of physical and biological controls is unknown and indeed unpredictable. Since phytoplankton cells and colonies range in size from a few microns to millimeters, changes in species composition due to competition and grazing could potentially restructure the size distribution within communities, affecting grazing efficiency among zooplankton and the nutritional value of the phytoplankton. Associated feedback effects on microbial communities in regions of OIF have often been observed (208). These types of changes at the base of a food web and in the microbial loop would affect energy transfer, trophic dynamics, and biogeochemical cycling throughout the Antarctic marine ecosystem and beyond.

Increased carbon export to depth is an intended consequence of OIF. Other (unintended) consequences could result from the trapping of nutrients below fertilized regions, alongside feedback effects, including deoxygenation and the production of other GHGs, e.g., methane and nitrous oxide (N_2O). The "nutrient-robbing" impact of OIF has garnered much attention because of its potential broad impacts on net productivity elsewhere in the world. The Southern Ocean plays a significant role in the transport of nutrients to lower latitudes (209), effectively regulating rates of global primary productivity, the efficiency of the BCP, and the transfer of energy to higher trophic levels (including fisheries). While OIF stimulates productivity, it simultaneously depletes stocks of major nutrients, limiting the amount of nutrients transported and consequently decreasing net primary production in regions outside of the fertilization area. In the Southern Ocean, the "nutrient-robbing" signal is exported to lower latitudes by the Subpolar Mode Waters and the Antarctic Intermediate Water, leading to nutrient-depleted surface waters in the tropics (201). Reductions in biological production and organic matter export have been well documented in waters outside the fertilization areas (201, 210). Indeed, recent modeling work has highlighted that when OIF is undertaken in the Southern Ocean, the greater nutrient consumption, coupled with ongoing climate stressors (e.g., increased stratification), leads to a reduction in higher-trophic-level organisms in the tropics (211). This cascading effect damages important fisheries in the tropical Pacific that are critical to coastal and island communities and for commercial exports—a major social equity concern. The consequences of "nutrient robbing" could be slightly mitigated if OIF were limited to the higher-latitude zones of the Southern Ocean, which are farther from where the intermediate and mode waters originate. However, this approach would provide a far smaller contribution to atmospheric CO_2 removal, while still having negative consequences (201, 211).

The biogeochemical effects of OIF include deoxygenation and the production of N_2O and methane (201). OIF increases oxygen consumption via the remineralization of the organic matter it produces. This compounds the deoxygenation already caused by global climate change through warmer waters and increased stratification. N_2O and methane are produced during the remineralization of organic matter produced by OIF, and both have a global warming potential greater than that of CO_2 on a 100-year timescale (300- and 20-fold, respectively). While the production of methane is a minor concern, since its highest production only occurs in anoxic waters, N_2O generation following OIF ranges from 5% to 12% of the equivalent CO_2 captured during a given OIF event (201).

Costs

The practicality of using OIF to mitigate anthropogenic carbon addition to the atmosphere has been questioned due to the difficulty of scaling it up to the magnitude that would be required for commercial application (212). Buesseler and Boyd (213) estimated that the effort needed (relative to the amount of iron used for fertilization) would be six orders of magnitude greater than that of any single experiment conducted in the Southern Ocean, and that the treated area would need to be 10 times larger than the Southern Ocean (which they defined as the area south of 50° latitude, equivalent to the area of Asia). The estimated cost of OIF per ton of CO_2 removed from the atmosphere varies by location, ranging from <US$100/ton on the shelf to >US$1,000/ton in offshore areas (214). For reference, global CO_2 emissions from fossil fuels in 2024 were 37.4 billion tons, and 41.6 billion tons when land use (e.g., deforestation) is accounted for (215).

Governance

One of the primary challenges of early OIF experiments lies in determining the legality of adding iron (a pollutant) to the ocean (216, 217). The UN addressed this issue in 1999, and OIF is now regulated by the London Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (or the "London Convention") (218). A 2013 amendment to the London Convention states that "An ocean fertilization activity may only be considered for a permit if it is assessed as constituting legitimate scientific research taking into account any specific placement assessment framework" (219). Therefore, no large-scale OIF mitigation projects can be implemented. National authorities are responsible for permitting OIF experiments, but several other international agreements also address OIF (220). The UN Convention on Biological Diversity (CBD) does not currently support OIF and the Kyoto Protocol of the UN Framework Convention on Climate Change (UNFCCC) does not allow OIF to be used for carbon credits. OIF is not addressed by the UN Convention on the Law of the Sea (UNCLOS), although it might fall under the UNCLOS definition of marine pollution. The Antarctic Treaty System has not specifically considered OIF; it does have an annex to its Protocol on Environmental Protection on the prevention of marine pollution, but this pertains to waste from ship operations (e.g., food, trash, and oil). The potential impacts of OIF on Southern Ocean ecosystems, food webs, and fisheries would also be of concern to CCAMLR.

OIF is the only geoengineering scheme tested *in situ* in the Southern Ocean, with the last experiment being in 2011 (221). While there has been a long hiatus in OIF experimentation worldwide, there is currently a resurgence of interest in researching geoengineering methods for marine CO_2 removal (mCDR) to alleviate both carbon accumulation in the atmosphere and ocean acidification resulting from the diffusion of CO_2 into the ocean. For example, in 2023, the US National Oceanic and Atmospheric Administration announced US$24.3 million in funding for such research endeavors (222), and the US Department of Energy (223) has allocated US$36 million for this joint program. Moreover, new computer technologies (e.g., digital twins) are being used in marine conservation management, including the planning of OIF strategies (224).

Part 2: Debunking geoengineering arguments

Geoengineering proposals are often accompanied by a set of recurring arguments intended to justify their exploration or implementation, particularly in the face of growing climate risks and perceived inaction. These arguments typically highlight geoengineering as a necessary, feasible, or even inevitable tool in the broader climate response portfolio. In this section, we examine four of the most common arguments advanced by proponents of geoengineering, evaluating the assumptions they rely on and the implications they carry for science, policy, and governance.

Argument 1: Mitigation is not happening fast enough

Current policies are insufficient to meet the emissions reductions required to keep warming below 1.5°C, as set out in the Paris Agreement. If countries fully implement their current policies, projections indicate a best-estimate warming of approximately 3°C by 2100 (41, 225, 226). If all current emissions reduction pledges are met, this estimate falls to around 2.5°C. However, countries have also communicated longer-term targets, which often aim to achieve net-zero CO_2 or total GHG emissions (227, 228). Taking these longer-term targets into account reduces the central warming estimate to 2.0°C (229). While this shortfall in climate action is concerning, it does not justify turning to geoengineering as a solution.

Although current policies and pledges do not yet guarantee 1.5°C compliance, they already provide a 1-in-5 chance of limiting long-term warming to 1.5°C, provided all commitments are met (226, 229). More importantly, these policies substantially increase the likelihood of limiting warming to below 2°C, with a 4-in-5 chance and a best estimate of 1.7°C. This underscores the need to accelerate mitigation efforts, rather than resorting to risky geoengineering approaches that fail to address the root causes of climate change.

Climate mitigation efforts are already scaling up, and rapid emissions reductions remain within reach using existing, proven technologies. One of the key flaws in the argument for geoengineering is that it underestimates the accelerating pace of green growth. Many clean technologies, such as renewable energy and electric vehicles, have already entered the rapid S-curve phase of adoption, where deployment scales exponentially as costs fall and efficiency improves (230, 231). Moreover, the Paris Agreement's 5-year ratcheting mechanism is designed to strengthen climate action over time, with countries currently required to submit more ambitious commitments following the first Global Stocktake. These mechanisms are expected to further increase the likelihood of limiting warming to as close to 1.5°C as possible.

Not only do proponents of geoengineering underestimate the potential for accelerated mitigation, but they also risk undermining it. By promoting unproven and potentially dangerous interventions, they distract from politically feasible, technically viable, and economically sound mitigation strategies that require stronger implementation urgently (47, 232).

Argument 2: It is our moral duty to look at "all the options"

Although there is an intuitive appeal to the notion that "all the options" should be considered in the search for approaches to address anthropogenic warming and its consequences, it is also important to recognize that certain options can carry a significant negative effect, termed here as "moral hazard". Moral hazards are understood as actions or steps that cause individuals, organizations, or societies to increase their exposure to risk because they believe they are not fully responsible for, and/or subject to, the consequences (233). We argue that geoengineering can constitute a moral hazard and, more broadly, constitute "mitigation deterrence". Here, we highlight two moral hazards associated with geoengineering: complacency and predatory delay.

While geoengineering is often framed as one of many tools in a broad climate strategy, its introduction into policy discussions actively competes with mitigation for attention, funding, and legitimacy. Actors, whether individuals or collectives, can focus on only so many priorities at once, and policymakers may be drawn to geoengineering because it appears to offer a quick fix that avoids difficult political trade-offs. Termed "mitigation deterrence" (110), this effect has been discussed by other researchers (234, 235). The problem is not merely complacency but also the misdirection of political and financial resources away from proven, necessary solutions. If geoengineering becomes the central focus, it risks sidelining efforts to phase out fossil fuels, and rather than continuing to explore a wide range of options, policymakers may decide that geoengineering alone can offer sufficient protection against climate risks. They could fall victim to what is termed the "single action bias"—the closing of searches for alternative solutions, once one step has been taken (236). Flood mitigation plans provide examples of the negative consequences of single action bias. The city of New Orleans long relied on levees and flood walls to protect it from storm surges, and did not support other actions, including wetland restoration or expanded evacuation plans; when Hurricane Katrina struck in 2005, the results of the levee failures were catastrophic (237). Similarly, smaller cities along the Missouri River, such as Hamburg, Iowa, Saint Joseph, Missouri and Fremont, Nebraska, also trusted the levee systems built in the past for protection, until the floods in 2019 led to failure or overtopping of the levees; the residents, who would have benefited from additional measures including resilience planning and evacuation drills, faced severe damage (238, 239). Catastrophic flooding in Kolkata, India and Fukushima, Japan, also indicates the failure of relying on dams and embankments alone.

Behavioral studies at the household level have demonstrated this bias in various settings. For example, homeowners in flood-prone areas who are less likely to purchase insurance or elevate their homes if they have simply stocked up on water, flashlights, and batteries (240), or consumers in a cafeteria who undertake fewer behaviors to reduce food waste (e.g., ordering less food) if they are told that uneaten food will be composted (241).

Predatory delay differs from the form of delays discussed above, which are largely unintended consequences of the complacency generated by particular actions. First introduced by Steffen (242), predatory delay refers to deliberate efforts by powerful institutions to slow the implementation of actions that address the root causes of problems to preserve their own financial and political power. Although some individuals within institutions may have genuine motivation to seek alternative actions, the overall goal of the institution is to postpone actions that would be costly to them, even if the actions would have broad benefits to society and the environment. Kramer (243) details the interactions of large firms and lobbyists to influence policymakers and regulatory agencies to create such delays. There is a lack of transparency associated with the funding of some geoengineering projects, which could leave them open to interference by bad or rogue actors, including the fossil fuel industry (107). Muffett and Feit (244) have detailed the funding of geoengineering research by fossil fuel firms, showing how this research is being used to support the ongoing production and utilization of oil, gas, and coal for several decades to come. Almond et al. (245) documented how energy centers at US universities that receive funding from fossil fuel companies promote "climate action-delaying tactics" that forestall "the transition to current renewable energy sources such as solar and wind" to a significantly higher extent than universities that refuse this type of funding. In this way, geoengineering could be compared to the tobacco industry's proposals for filter cigarettes as a way to reduce the risk of cancer without reducing the consumption of tobacco (246).

There is also a growing body of literature on how geoengineering funding (including from super-rich individuals and foundations), while being based on a perception of "moral duty", may lead to the establishment of undemocratic values and power relations (106), increased unilateralism (247), misconstrued morals and public acceptance (248, 249), and a lack of awareness regarding international conflict versus cooperation (250).

Argument 3: Geoengineering will "buy us time" to adapt and find other solutions

Geoengineering approaches are frequently presented as temporary measures to delay climate change while societies develop long-term solutions. However, this argument fails to account for the contrasting temporalities between geoengineering deployment and mitigation efforts. Overwhelmingly, geoengineering concepts and methods are in the early-to-middle stages of research and design, meaning that their large-scale implementation remains speculative and probably decades away. Even if they worked as intended (which is highly uncertain), they would still require extensive political deliberation, governance frameworks, ethical considerations, resource allocation, and infrastructure development before deployment. Therefore, geoengineering will not "buy us time" in the near term; rather, it diverts time and limited resources toward uncertain technological fixes that are unlikely to be implemented soon, if at all. In contrast, many mitigation technologies already exist and are ready to be scaled up locally and globally. Investing in mitigation is a direct response to the urgency of addressing climate change, while geoengineering remains a gamble, with long- and uncertain-time horizons. Therefore, it makes more sense to invest in improving and scaling existing technologies that reduce emissions than to work on speculative technologies that do not address emissions. With an increased focus on the implementation of existing technologies, we can make substantial global progress on reducing emissions, with limited need for additional new technological solutions.

Argument 4: Geoengineering will prevent tipping points from being crossed

The concept of "tipping points" in the climate system has been a subject of debate for several years. While many studies have emphasized the severe risks associated with crossing these thresholds (147, 232, 251, 252), others have argued that the focus on tipping points can create confusion and, potentially, lead to poor decision-making regarding climate action and environmental protection (253).

The polar regions are home to, or have a direct influence on, four of the five most vulnerable climate tipping points: Greenland Ice Sheet collapse, West Antarctic Ice Sheet collapse, abrupt permafrost thaw, and the collapse of the Labrador–Irminger Subpolar Gyre (42, 251). These Earth system components are at risk of crossing their tipping points with ~1.5°C of warming, and the risk increases as temperatures rise. Some may have already crossed these thresholds (152, 232, 254, 255).

While several studies have framed SRM as a means to delay the crossing of potential tipping points (256–259), others have indicated that it is less effective than GHG mitigation strategies due to the uncertainties and risks involved (260). Moreover, these studies have relied on simplified scenarios that neglect sociopolitical factors that could cause harm or raise ethical dilemmas, which would further restrict the potential of geoengineering as an emergency solution (261–263).

Geoengineering interventions face significant challenges due to the limited timeframe for their deployment. The urgent need for immediate action to prevent the crossing of tipping points necessitates the rapid implementation of strategies. However, the development and application of geoengineering methods would require extensive research, planning, and international cooperation, making it impossible to meet the narrow timeframe available.

Given the substantial uncertainties and challenges associated with geoengineering, it should not be considered a reliable solution for preventing the crossing of Earth system tipping points. Therefore, the focus should remain on aggressive emission reduction strategies and robust adaptation measures. The necessarily limited amount of public research funding available needs to be focused on developing a deeper understanding of Earth system tipping points to minimize associated risks, and thus on the fundamental understanding of the natural systems involved, rather than on researching the impacts of large-scale interventions in these poorly known systems.

Part 3: International governance and decision-making

In Part 1, we touched on governance matters that would need to be overcome before the deployment of any geoengineering intervention. In this section, we discuss more broadly the existing international governance arrangements in the polar regions and whether or how they are set up to perform an essential role in preventing or setting strict terms for these interventions. Notably, geoengineering presents unique obstacles to effective governance that are not found in other areas of international environmental collaboration (e.g., transnational river basin management or stratospheric ozone management). First, the approaches differ greatly between the technology-centered geoengineering advocates and the institutional and legal frameworks of international regulatory agencies, so they lack common sets of references on which to base planning. Second, stakeholders who seek approval from governance authorities operate on short-term timeframes, while researchers and government regulators adopt medium- and long-term timeframes to address the numerous uncertainties in this area. Finally, geoengineering promoters emphasize trade-offs between risks, which conflict with the precautionary priorities of environmental governance. Together, these barriers severely impede the discussions that are a necessary precursor for effective governance (264).

Antarctica and the Southern Ocean

Antarctic governance is managed through the Antarctic Treaty System, which uses a consensus-based model for decision-making (265, 266). The Antarctic Treaty, which entered into force in 1961 and currently has 58 signatory states, sets Antarctica aside as a continent for peace and science. The Protocol on Environmental Protection to the Antarctic Treaty (hereafter "the Protocol"), which entered into force in 1998, states that activities in the Antarctic Treaty area (the areas south of latitude 60°S) must be planned and conducted to limit adverse impacts on the Antarctic environment and dependent and associated ecosystems, and to avoid, among other things (i) adverse effects on climate or weather patterns; (ii) significant adverse effects on air or water quality; (iii) significant changes in the atmospheric, terrestrial (including aquatic), glacial or marine environments; and (iv) detrimental changes in the distribution, abundance or productivity of species or populations of species of fauna and flora [Article 3(2a and b) (133)]. The Protocol also states that activities in the Antarctic Treaty area must be planned and conducted on the basis of information sufficient to allow prior assessments of, and informed judgments about, their possible impacts on the Antarctic environment [Article 3(2c) (133)]. If there is insufficient information on the likely impacts, the use of geoengineering technologies would be contrary to the Protocol and consequently unlikely to receive authorization to proceed.

All activities undertaken within the Antarctic Treaty area must be subject to an Environmental Impact Assessment (EIA), as stipulated in Annex I to the Protocol (267). The level of the EIA prepared by the Party undertaking the activity will depend on whether the anticipated activity is likely to have an impact that is less than, equal to, or greater than "minor or transitory". The Protocol does not define these terms; however, any geoengineering activities would almost certainly trigger the highest level of EIA, known as a Comprehensive Environmental Evaluation (CEE). To date, CEEs have been undertaken for activities such as station construction, but some proposed geoengineering projects are of a scale several orders of magnitude greater. The Protocol also sets out monitoring requirements to ensure that the impacts of the activity are consistent with the Protocol, and to provide information that is useful for minimizing or mitigating impacts, and, where appropriate, information on the need for suspension, cancellation, or modification of the activity (Annex I, Article 5).

International consultation is key to Antarctic governance and, in a system driven by consensus-based decision-making, controversial or unproven geoengineering activities have a very low likelihood of approval. Promoters of geoengineering from the ~139 countries that have not acceded to the Antarctic Treaty (representing ~35% of the global population) are not obligated to comply with any of these requirements. However, non-Treaty parties are unlikely to be able to support independent expeditions to the continent, and the use of large-scale geoengineering methods without sufficient consultation with the Antarctic Treaty Consultative Meeting (ATCM) would probably result in an international outcry (134, 268), as the ATCPs closely guard the status of the Treaty and their rights as Parties.

In practice, no Party project for which a CEE has been presented to the ATCPs has been prevented from going ahead (albeit sometimes with significant delays), including some projects involving what elsewhere might be considered high-impact activities (269). Given the potential global impact of using large-scale geoengineering methods in Antarctica and the international effort needed to deliver them, any concerns may not only be raised in the ATCM system, but may also face challenges outside it (e.g., via the UNFCCC, UN Environment Programme, or UN General Assembly), which the existing ATCPs would want to avoid.

Under Article 7 of the Protocol, which bans mineral resource activities except for scientific research, the ATCM has blocked commercial extraction in Antarctica. Given the large scale of proposed Antarctic geoengineering, the ATCM could take similar action. Almost 20 years after its agreement, Annex VI to the Protocol (Liability arising from Environmental Emergencies; 2005) has yet to enter into force. Once enacted, however, it would impose a liability on non-state operators to pay for a "response" (clean-up) for environmental damage caused. Even if private, rather than state, operators stepped in to undertake geoengineering activities, the requirement for a CEE and to obtain a permit from the relevant Party would remain the same.

Overall, the prospects of addressing proposals for geoengineering activities in Antarctica depend on the environmental impact assessments conveyed to the Antarctic Treaty System and the political will of its members or parties to the agreements to give effect to the obligations they have set themselves. The Antarctic Treaty System's agreements (including CCAMLR with respect to marine living resources) constitute a set of rigorous governance arrangements that are wholly underestimated by geoengineering proponents.

At the most recent ATCM and CEP meeting (Milan, 23 June - 3 July 2025 (270)), on the basis of a paper by SCAR, the CEP advised the ATCM that a precautionary approach should be taken towards geoengineering activities and that, at this point, geoengineering methods in the Antarctic should not be conducted due to their unknown environmental consequences. The ATCM endorsed the recommendation to adopt a precautionary approach towards all geoengineering activities in the Antarctic area. Most ATCPs supported SCAR's conclusion that, based on the current state of knowledge, none of the options outlined in the papers met essential criteria to be considered safe, responsible or feasible and should not be considered for Antarctica. They also emphasised that geoengineering should not be considered as a solution to climate change in Antarctica.

The Arctic

Unlike the Antarctic, the Arctic region falls predominantly within national jurisdictions (see: https://www.durham.ac.uk/media/durham-university/research-/research-centres/ibru-centre-for-borders-research/maps-and-databases/arctic-maps-2024-january/Map-1-IBRU-Arctic-map-04-01-24-(revised-Russia-claimed).pdf). There are four "high seas" areas, as defined by UNCLOS, including the central Arctic Ocean itself; however, this represents a small fraction of the total Arctic Ocean area. While the governance of activities and their impacts at the surface and in the water column within high seas areas resides with a variety of existing international mechanisms, such as the IMO and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) and the emerging UN High Seas Treaty, the governance of activities and their impacts at and below the seafloor may change in the future. Many coastal Arctic states are conducting long-term research to establish the northward reach of their continental shelf, thereby seeking to provide evidence to extend their national seabed boundaries, in many cases out into the central Arctic Ocean. This is all in line with established UNCLOS requirements and practices. There is no timetable for the resolution of claims arising from the submission of this evidence.

All land in the Arctic is within nationally regulated and internationally agreed-upon boundaries. Consequently, the dominant legal and regulatory governance mechanisms, including those that would relate to geoengineering, are overwhelmingly those of the eight

Arctic states themselves: the United States, Canada, the Kingdom of Denmark (including Greenland), Iceland, Norway, Sweden, Finland, and Russia. The major international organization in the region is the Arctic Council, created in 1996 to provide a high-level forum for promoting cooperation, coordination, and interaction among the Arctic states and the Permanent Participants (PPs), namely, six representative organizations of Indigenous peoples. State and non-state Observers also participate in discussions at the discretion of Member States and PPs. The Council offers a space for discussion and mechanisms for addressing issues of common concern, with a special emphasis on protecting the Arctic environment and promoting sustainable development. Established by the Ottawa Declaration, the Council is not a Treaty organization under the terms of the Vienna Convention—unlike the Antarctic Treaty. There are well-established procedures for both state and non-state organizations to apply for Observer status with the Arctic Council, although approval requires consensus from all eight Arctic States. Unlike Antarctica, where no state has legal jurisdiction, there is no opportunity for states to unilaterally join the Council, which by definition is limited to states with territory within the Arctic Circle.

The Arctic Council has strongly addressed governance issues across the Arctic internationally, although rapid climate change and recent geopolitical tensions have placed it under unprecedented pressure (271). Nevertheless, history shows that cooperation on scientific and environmental issues is vulnerable to disruption by overall distrust and geopolitical dynamics between member states (272). Following Russia's full-scale invasion of Ukraine in 2022, the activities of the Arctic Council's six Working Groups halted as all member states except Russia announced their non-participation. Under Norway's current chairship (2023–2025), significant working-level activity has resumed across the Working Groups. However, the organization has yet to resume in-person ministerial and senior officials' meetings involving all eight members. With the new United States administration of 2025, the coming years are likely to remain challenging, with increasing geopolitical uncertainty and persisting tensions with no clear resolution in sight.

The Arctic Council is not a regulatory or law-making body, as legislative authority remains within the national jurisdictions of its member states. The Council has never sought, nor do its members intend for it to have, the power to enforce collective decisions. Other organizations, including the North East Atlantic Fisheries Commission, have the authority to adopt conservation and management measures across portions of the Arctic Ocean, but only within the scope of agreed-upon national jurisdiction. While the Council's work has covered an extremely wide range of issues connected to environmental, ecosystem, and human change in the Arctic—assessing evidence and producing guidelines and best practices—it has chosen not to look specifically at geoengineering.

Under the auspices of the Arctic Council, the eight Arctic states have negotiated the following legally binding international agreements: maritime search and rescue; marine oil pollution prevention and response; and Arctic science cooperation. These are implemented by the states within their national jurisdictions, not through Council mechanisms. These agreements may have relevance to proposals for geoengineering activities in the Arctic, including their prohibition in the region.

While the Arctic Council has relatively weak oversight of international waters where, for example, any proposed silicate spheres could be located, these efforts almost certainly would require activity in national (or asserted national) waters. Objects that drift from international waters into the territorial waters of a member state (273) come under that state's jurisdiction. Any decision for the Arctic Council to address geoengineering would require both the championing of an incoming chairship (e.g., Denmark in 2025–2027 or Sweden in 2027–2029) and the consensus of all eight Arctic states during the priority-setting process ahead of each 2-year rotating chairship.

As many parties view the Arctic as an opportunity for economic growth and resource extraction, and as a zone of geopolitical tension, there is little prospect of long-term multilateral and low-tension collaboration on geoengineering at present (272). While governance responsibility predominantly lies with the individual Arctic States—either individually or collectively—the effects and impacts of geoengineering cannot be guaranteed to come from or stay within such territorial boundaries.

In contrast to the Antarctic, the Arctic is home to Indigenous communities whose traditional way of life is under increasing pressure from climate change and social and cultural challenges associated with geopolitical and post-colonial development. Strategies that seek to engineer a reduction in the rate of sea level rise via glacier modifications address neither climate impacts nor local cultural challenges. In many cases, these interventions likely worsen local socioeconomic and environmental conditions by potentially putting further pressure on activities such as marine harvesting of fish and mammal species with, for example, increased underwater noise and disturbance of wildlife populations on land, while offering no substantial benefit to local communities. On the other hand, resource extraction of minerals to support the green transition and agriculture, as well as the development of renewable power resources which the Arctic region is rich in, can benefit both local and distal populations and represent a far more sustainable path for climate change mitigation both locally and globally with additional economic benefits for local Arctic populations if implemented sensitively.

It is pertinent to ask: *why* would a nation such as Greenland embrace a geoengineering solution to sea level rise, for example? The sea level is not rising there—rather, the loss of ice sheet mass is causing gravity-induced sea level lowering (274). Moreover, Greenland's contribution to global GHG emissions is small and its local ecosystems would be at risk from geoengineering.

In summary, both the Arctic and the Antarctic lack the effective governance mechanisms needed to offer protections against the significant potential harms of geoengineering. We wish to underscore this commonality, while recognizing the significant differences between the two regions—the greater strength of national institutions in the Arctic; the greater dominance of a single treaty in the Antarctic; the wider range of economic interests in the Arctic; and the absence of historic Indigenous peoples in the Antarctic, just to mention a few.

Part 4: Protecting the polar regions without geoengineering

In this section we offer an alternative approach to protect the polar regions that does not rely on physical interventions in natural systems or the intentional use of pollutants. We do not propose these as isolated solutions or quick-fix interventions, but rather as components of a transformation of humanity's relationship to our planet, known as "climate-resilient development". This transformation comprises shifts in major systems, such as energy systems, land use systems, and food systems, which can be best addressed jointly (275). We focus on two components particularly relevant to polar regions: decarbonization and maintenance of protected areas.

Decarbonization

Rapid decarbonization to "net-zero" emissions by mid-century, and into "negative emissions" thereafter will lead to a rapid and permanent climate response (the so-called "Zero CO_2 Emissions Commitment" or ZEC) (276). This decarbonization will require significant changes in energy, land use, and food systems. The global warming climate system is likely to stabilize (i.e., global surface temperatures cease increasing) within 20 years of net zero CO_2 (43). This assessment is good news for the polar regions across various systems and realms. Not all changes can be stopped, but their rates of change would be comprehensively reduced if and when net-zero emissions are reached.

Two investigations have underlined the environmental benefits of net-zero CO_2 and climate stabilization. Rintoul et al. (21) "hindcasted" two scenarios from the perspective of 2070: one with unabated emissions and a second with ambitious decarbonization leading to net-zero emissions. In the latter scenario, the global temperature stabilized at 0.9°C above pre-industrial levels, as opposed to 2.6°C in the former (similarly for Antarctic air temperature). These scenarios were matched by effective governance of Antarctica and the Southern Ocean under ambitious decarbonization, as opposed to ineffective policies. The relative benefits of decarbonization, based on literature and expert opinion, proved significant in all cases (21). The Antarctic contribution to sea level rise by 2070 was limited to 6 cm, as opposed to 27 cm under high emissions [see also (277)]. Southern Ocean temperatures increased by only 0.7°C as opposed to 1.9°C. Sea ice loss was restricted to 12% of present levels, as opposed to 43%. Ice shelf volume was reduced by only 8% as opposed to 23%. In terms of ocean acidification, decarbonization retained surface super-saturation for aragonite, while continued fossil fuel burning and deforestation led to waters that are corrosive to the aragonite shells of pteropods. Biological invasions were restricted to twice those of today, versus tenfold. Ecosystem failure occurred under both scenarios, but under unabated fossil fuel burning, penguins and krill were adversely affected. With enhanced policy, far fewer people were present in the region, with an accompanying reduction in marine resource extraction. Rintoul et al.'s (21) simple vision for Antarctica is appealing, as it explains how every polar system can be helped by decarbonization, and certainly to the extent that direct intervention (or geoengineering) would be unnecessary.

A similar assessment of the Antarctic Peninsula explained the environmental consequences of limiting global warming to 1.5°C relative to pre-industrial levels (278). Such an outcome, under rapid deep decarbonization to net-zero CO_2 globally by mid-century, would benefit all realms of this environment. This study compared the present situation (1.2°C in 2019) and that at 1.5°C, revealing the magnitude of the "best case" changes. For example, in a 1.5°C scenario the number of days per year when surface air temperatures exceed 0°C would increase from 25–80 to 35–130. While the resulting melting may lead to ponding of water on floating ice shelves, a dramatic loss of ice shelves is not expected. Sea ice would be more limited, but it would remain around the Peninsula, especially in the South. Thus, the sea ice and krill-dependent food web would migrate southward, leaving the northern Peninsula with an increase in fur seals, elephant seals, and gentoo penguins.

While such changes are unwelcome, being an indirect but obvious consequence of fossil fuel burning, they alone would not necessitate an artificial geoengineering intervention at the scales being proposed, and none of the interventions would address these changes. Further warming would probably bring an increase in "extreme events", such as atmospheric and marine heatwaves (15) and continued sharp reductions in sea ice. However, while much of the natural polar environment would be altered or displaced, it would still be present in a manner deserving of environmental protection (e.g., with respect to its marine biodiversity). Indeed, under the ZEC scenario, once net zero has been achieved negative emissions would rapidly (within ~20 years) act to cool the planet, potentially reversing changes under 1.5°C warming. This scenario is already technically, financially, and politically possible (51, 279), and it represents our best means of protecting the Antarctic environment, with major co-benefits for human health and planetary habitability.

The Arctic situation may be profoundly different. Continued global warming will result in enhanced regional warming here, leading to further sea-ice loss, permafrost thawing, and ecosystem damage, all of which will adversely affect the livelihoods, cultures and living environments of Indigenous peoples. Global climate stabilization offers the best chance to protect the Arctic; however, significant further change may already be unavoidable and, as this paper highlights, geoengineering is not a solution.

Protected areas across the polar regions

Well-managed protected areas, especially those that are highly protected—the equivalent of International Union for Conservation of Nature (IUCN) Categories I or II (280)—significantly benefit biodiversity and ecosystem services. These benefits include higher species richness, abundance, and functional diversity within protected areas and ecological spillover that benefits biodiversity outside the protected area. Substantial evidence exists for these effects on land (281–284). Marine protected areas have similar benefits: evidence-based syntheses and specific studies demonstrate higher biomass/abundances and functional diversity of species within strictly protected areas (compared with outside), along with ecological and fishery spillover (i.e., the outward emigration of individuals that benefits a fishery) (285–288).

Although climate change threatens their effectiveness (289, 290), protected areas provide significant benefits to biodiversity under climate change in both terrestrial and marine systems (291–293). Moreover, protected areas can mitigate the effects of climate change itself, by ensuring the maintenance of ecosystem services such as carbon sequestration (294), and enhancing ecosystem resilience by minimizing other impacts (28). Consequently, protected areas remain a central component of the mitigation response to climate change impacts on biodiversity. Key priorities include various strategies to grow, connect, and manage the network of protected areas, and to improve their overall individual efficacy (295–298).

The climate change mitigation benefits of protected areas have also been recognized in the Antarctic and the Arctic (22, 299); however, it is important to acknowledge the substantial differences between the two regions (300). Although protected areas cannot entirely mitigate impacts such as ocean acidification (301), they can play an important role. Moreover, reducing GHG emissions will mitigate impacts such as ocean acidification, whereas geoengineering activities that fail to reduce atmospheric CO_2 concentrations will not, leaving biodiversity and ecosystem services exposed to a growing threat.

To be effective in a climate change impact mitigation framework, polar protected areas will need broader coverage of biodiversity features and areas, greater connectivity, and more flexibility in their boundaries in response to changing ecological circumstances. Their greatest challenge is ultimately political. For example, the ATCPs and the Members of the CCAMLR have been slow to designate protected areas (302), and there are growing difficulties in protected area discussions in both of these Antarctic Treaty system bodies (303). However, previous difficulties in international environmental agreements have been overcome to great success, such as the 1987 Montreal Protocol to phase out the production of substances responsible for ozone depletion and the 2016 CCAMLR agreement to designate the Ross Sea region as a Marine Protected Area.

Summary

Over the past three years, polar geoengineering has gained increased media and public attention, with various ideas largely based on computer modeling and limited field studies aiming to increase Arctic sea ice, enhance atmospheric reflectivity, halt the transfer of warmth from the ocean to the grounded ice sheet, and slow the flow of grounded ice into the ocean. In this paper, we have critically assessed five such approaches, identifying significant challenges across six key categories.

1 Scientific feasibility

All five proposed concepts are based on the assumption that natural systems can be forcibly controlled through intervention. However, each method has significant oversights that raise serious doubts about whether implementation would achieve the desired outcomes. A key example is Proposed Concept 4—Slowing Ice Sheet Flow—which involves drilling to the base of ice streams to remove basal water and reduce ice flow. Even if water is successfully extracted, it is likely to be replaced by groundwater or redirected from other sources, requiring continuous drilling of new holes. Our limited understanding of Antarctica's subglacial system, and polar systems in general, makes effective planning for such efforts highly uncertain.

2 Environmental risks

One of the central themes throughout this paper is the significant and compounding uncertainties associated with the climate and biogeophysical impacts of the five reviewed geoengineering options. These uncertainties span direct, indirect, and systemic effects and remain vast and largely unquantified. In some cases, the proposed geoengineering intervention uses a direct pollutant, such as in the case of glass microbeads used to increase Arctic sea ice albedo, the SO_2 used for atmospheric aerosol injection, and the iron used for ocean fertilization. In other cases, the interventions disrupt weather patterns and the circulation of ocean currents and nutrients. Without rigorous quantification of error bounds and a significant reduction in these uncertainties, it is challenging to foresee a scenario in which decision-makers could proceed with confidence. In fact, the inability to resolve fundamental uncertainties about the impacts may represent one of the most compelling arguments against deploying geoengineering interventions at present.

3 Financial costs

In addition to environmental costs, there are significant and potentially prohibitive financial costs associated with geoengineering. All of the proposed ideas would require funding at a scale of many billions of US dollars, which is presently unavailable through either national or international arrangements. It is unknown where the funds needed to pursue geoengineering interventions would come from, but they would dwarf present scientific budgets. While fundamental research in glaciology contributes to our understanding of climate dynamics, informs mitigation strategies, and supports adaptation planning, large-scale geoengineering research seeks to develop interventions that carry high levels of uncertainty and risk. If these funds were made available, they would be far more effectively spent on fundamental climate research and efforts to decarbonize rapidly.

4 Governance challenges

Currently, no legal or governance framework supports these geoengineering proposals. In the case of Antarctica, such arrangements are offered through the CEP and ATCM. At its most recent meeting the CEP advised that geoengineering methods in the Antarctic should not be conducted. The ATCPs have largely taken this advice noting that such geoengineering has no place in the region, though with some also noting that any such proposals would need formal CEEs before commencing any work. Furthermore, any expansion of governance arrangements in both the Arctic and the Antarctic hinges on the consent of the majority of or all affected states. Current research on the interaction between international politics and geoengineering indicates that the latter will either prove to be politically infeasible or could even contribute to rising geopolitical tensions if deployed unilaterally. Additionally, while reducing carbon emissions is both feasible and undeniably beneficial, international coordination on this effort has been slow and challenging. Given these difficulties, it is even less likely that consensus could be achieved on geoengineering interventions that carry far greater uncertainties and potential risks.

5 Scale and time constraints

Limiting the escalation of severe climate-related risks demands that we cut GHG emissions to net zero by mid-century. It has been suggested that geoengineering approaches could be used as a temporary measure to "buy time" while societies develop long-term climate solutions. However, this argument overlooks the stark contrast in timelines between geoengineering and mitigation efforts. Most geoengineering approaches are still in the early stages of research, with large-scale implementation probably decades away, if they prove viable at all. Even assuming they work as intended, their deployment would require extensive political negotiations, governance structures, and infrastructure investments, making them an uncertain and delayed response to climate change. In contrast, many mitigation technologies already exist and can be rapidly scaled up. Investing in proven emissions-reduction strategies directly addresses climate change now, whereas geoengineering diverts attention and resources toward speculative solutions with uncertain outcomes.

6 The risk of false hopes

Geoengineering proposals offer false hope that the effects of global warming can be avoided by means other than rapid, deep cuts to GHG emissions. Two key risks are (i) complacency, in which decision-makers focus on geoengineering at the expense of proven decarbonization strategies, and (ii) predatory delay, in which powerful actors may promote geoengineering to justify continued emissions and preserve their own financial or political interests under the pretense of climate action.

All five proposed geoengineering interventions we have discussed here are extremely unlikely to mitigate the effects of global warming in polar regions and are likely to have serious adverse and unintended consequences. The only realistic and effective approach is rapid and sustained decarbonization to net zero. Given the limited time available, our full attention must remain on proven strategies rather than speculative interventions with unproven benefits and substantial risks.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsci.2025.1527393/full#supplementary-material

Statements

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Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

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Conflict of interest

JRu is employed by the Polar Regions Department of the United Kingdom Foreign Commonwealth and Development Office (FCDO).

KRH is the Chair of Antarctic Science Ltd. and the Honorary Secretary of the Challenger Society for Marine Science.

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