Targeted Geoengineering: Local Interventions with Global Implications

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Special Issue Article

Abstract

Targeted geoengineering aims to tackle a global scale impact of climate warming by addressing local or regional systemic interventions. We consider three examples: conserving the West Antarctic ice sheet by limiting rates of ice discharge or increasing snow accumulation, thereby reducing global sea level rise; transforming the Arctic permafrost zone into steppe grassland; raising the albedo of Arctic sea ice. There are important differences between targeted interventions and archetypal solar geoengineering, which ideally would have global governance structures, while some targeted interventions may be done entirely under the accepted purview of small numbers of nation states. For example, the West Antarctic ice sheet is governed by the consultative members of the Antarctic Treaty. Of the interventions we look at, only ice sheet conservation seems viable and efficient relative to solar geoengineering. Many important treaties and conventions rely on the precautionary approach. While at first glance this principle seems to argue against targeted interventions, we argue that it may in fact do the opposite. Given the existence of irreversible thresholds in many natural systems, the precautionary approach may be better upheld by a targeted intervention that prevents a system from changing in ways that cannot be undone.

Policy Implications

- Doing solar geoengineering would ideally need at least near-global consensus, while targeted approaches require only a subset of states to agree on them. For example, Russian and Canadian policies could change the carbon released from thawing permafrost. Similarly, Greenland's ice sheet would be the primary responsibility of the Greenlanders. For the Antarctic ice sheet, the 29 Consultative Parties to the Antarctic Treaty would determine if such work was consistent with the agreements, especially the Madrid Protocol.
- Targeted geoengineering is done on regional scales but aims to conserve the various parts of the global climate and earth system. Hence, as with solar geoengineering, it is a proactive measure. Many international treaties aim to preserve the status quo, prohibiting certain activities, and encourage conservation.
- Targeted geoengineering involves various amounts of civil engineering that could create damage locally. Environmental impact assessments are demanded by 'The Greenland Home Rule for Greenland' and the Madrid Protocol in Antarctica. In the case of Arctic sea ice, all states have guaranteed access to navigation routes, but the Law of the Sea Conventions provides for the construction of artificial structures of limited extent.
- There is considerable scope for raising awareness of the inherent value of preserving the permafrost and Greenland ice sheet environment that is at least nominally held by the minority indigenous peoples of the far North. Monetizing these resources in the style of Payments for Ecosystem Services (PES) would provide a much more sustainable and equitable source of income than present efforts to extract mineral and fossil fuel resources from the Arctic.
- The United Nations Framework Convention on Climate Change (UNFCCC) concept of shared but differentiated responsibilities may imply that funding for cryosphere conservation should come from rich nations, and enlightened self-interest would point towards tackling rising sea level and other impacts by conservation rather than defending their own coastlines.
- Institutions based in, and representative of local Arctic people, such as the University of the Arctic, could and should play an important role in empowering and educating the region on the value of the ice sheet and permafrost to the whole planet, in addition to the region itself.

1. What is targeted geoengineering?

The definition widely accepted for geoengineering was standardized by the Royal Society report in 2009: 'the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change' (Shepherd and Working Group on Geoengineering the Climate, 2009, p. 1). This was discussed on two strands: solar radiation management (or modification) and carbon dioxide removal. The Intergovernmental Panel on Climate Change (IPCC) (2018) prefer the term 'remedial measures' citing ambiguous definitions of geoengineering. The differing terminologies also reflect the emerging nature of geoengineering in terms of science, technology, and governance. One of our main points here is to contrast these standard global approaches with measures designed to avert or reverse potentially catastrophic thresholds in various parts of the earth system (Lenton et al., 2019).

The cryosphere is a key element of the global climate system, with 5 of the 9 tipping points identified by Lenton et al. (2019), and which they argue are essentially too late to address by standard political processes that usually require 30-year timescales. The ice/water phase change at the freezing point represents an important threshold in the climate system, as the change from ice to water is associated with major changes in albedo and other properties.

The albedo of ocean water is about 0.06, the albedo of ice and fresh snow around 0.5–0.9. The physical impenetrability of an ice layer on the ocean in the form of sea ice means mass and energy exchange between water and atmosphere is fifty times lower than without sea ice.

Permafrost stores more than twice the present-day atmosphere's load of carbon. That carbon is inert while permafrost is frozen, but on thawing will be released either as CO_2 or CH_4 to the atmosphere. Such a huge reservoir becoming a source of carbon in the coming centuries could dwarf efforts to mitigate anthropogenic emissions. Indeed, estimates (Yumashev et al., 2019) of the economic consequences from the release of permafrost carbon and the reduction of Arctic albedo amount to \$23 trillion for a 1.5°C rise in mean global temperature above the pre-industrial, to \$66 trillion for Paris Nationally Determined Contributions (NDC) scenarios by 2300.

Much of West Antarctica is susceptible to rapid collapse because it stands on bedrock that deepens inland. The floating ice shelves that surround and stabilize the grounded ice sheet have been dramatically thinned in recent years by basal melt caused by the intrusion of warm ocean waters, leading to an acceleration and potential destabilization of several important glaciers (Turner et al., 2017). The unstable parts of the ice sheet have the potential to raise sea level by 5m or more over the coming centuries (Deconto and Pollard, 2016). Because of the strong hysteresis in the ice sheet system, such a collapse would be effectively permanent. If we lost any of the Earth's large ice sheets, the climate would have to be cooled far below its present state for thousands of years in order to regrow the ice sheet to its present volume.

The changes in the cryosphere have local, regional and global climate impacts. Thus, any decline in them will have global repercussions, and hence taking measures aimed at preserving them against thaw, also has global consequences and hence constitutes geoengineering. Additionally, the impacts of these thaws will have very serious consequences: loss of coastal land under business as usual emissions scenarios has been costed at US\$50 trillion/year (Hinkel et al., 2014), while building and maintaining coastal defences to prevent that loss of land would still cost about US\$50 billion/year. The cost of carbon release from permafrost also runs in the trillion per year range – even assuming it would not cause outright civilization collapse (Chen et al., 2020; Yumashev et al., 2019). Loss of summer sea ice in the Arctic Ocean would have less dramatic impacts on the global environment, but would destroy or threaten many ecosystems and species. Less extensive sea ice would lead to increased shipping, tourism, natural resource extraction and trade. Furthermore, traditional activities of Arctic indigenous peoples would be detrimentally impacted by reduced temporal and spatial extent and quality of sea ice, including mobility and hunting, and consequently a decline in the relevance of traditional knowledge (AMAP, 2017b; Carson and Peterson, 2016).

Proposals have been made to preserve each of these three elements of the cryosphere: sea ice, permafrost, ice sheets. Thus, they constitute a different class of geoengineering than solar radiation management or carbon dioxide removal, which we term targeted geoengineering. Targeted geoengineering has important differences from global approaches. These differences affect how they might be governed and their legal, ethical and societal implications.

2. Examples of targeted geoengineering interventions

Before discussing what are targeted geoengineering interventions, it is worth mentioning some that are not, despite first appearances to the contrary. One of these is the idea of wrapping and insulating individual ice bodies or glaciers, for example, because of tourism. This small-scale approach has no global climate significance and hence does not qualify as geoengineering. Another one is cloudseeding used to modify severe storms, making precipitation as desired and is a purely local-scale intervention of weather, not climate. It is done routinely by 50,000 communes in China to mitigate agricultural crop damage (Edney and Symons, 2013). There has been a suggestion to do large-scale cloud seeding across the Tibetan Plateau by some provincial engineers, but this has no national support in China (Moore et al., 2016), and likely will not be done at scale.

The Australian government wants to save the Great Barrier Reef, and is funding research into how marine cloud brightening could locally cool the ocean, and prevent coral bleaching. According to our definition this is not really a targeted geoengineering intervention because although it addresses a localized region, the effects of cloud brightening are very unlikely to have significant – or measureable – global climate impacts. However, some studies (e.g. Ojala, 2015; Slocum, 2004) stress the importance of making climate change meaningful for people so that they would be motivated to act. The high price of action means that climatically insignificant glaciers or coral reefs that we just happen to love cannot be rescued. But emotional attachments and symbolic significance would likely play key roles in the design of any intervention on key systems such as ice sheets and permafrost.

Having given examples of ideas which are either definitely not, or possibly not targeted geoengineering as defined earlier, we now turn to ideas that qualify as targeted geoengineering.

Arctic sea ice management

The idea behind sea ice management is to target Arctic sea ice directly. Ice911 (https://www.ice911.org) proposes to increase the surface albedo of sea ice by adding highly reflective silica spheres to the surface. The silica balls are plausibly environmentally inert, being made of sand. Ice911 claims that the spheres are not small enough to damage marine or human life (https://www.ice911.org/safety-testing). Pilot studies have been conducted in the Canadian Arctic and their small-scale properties have been used in a global climate model to ascertain what impact they would have on the persistence of the sea ice in the spring melt season (Field et al., 2018). Deployment is envisaged in the Beaufort Gyre, where sea ice circulates for several years before exiting the Arctic Ocean, and would be during early ice formation in the autumn over an area of perhaps 100,000 km^2 (0.5% of the Arctic Ocean) using bulk carrier ships. If this relatively small area affects the general pack ice then the idea appears to be feasible both on engineering and economic grounds.

Increasing Arctic sea ice simply by pumping sea water to the surface and allowing it to freeze was examined in detail by Desch et al. (2017). Further modelling (Zampieri and Goessling, 2019) suggests it would in principle be feasible to increase ice thickness, and Desch et al. (2017) estimate that a 1m increase in thickness over 10% of the Arctic using local wind power from buoy-mounted turbines would cost about $50 billion per year. However, Zampieri and Goessling (2019) report no cooling of lower latitudes in simulations using the Alfred Wegener Institute Climate Model as a consequence of the intervention in the ice-albedo feedback, and hence 'cast doubt on the potential of sea ice targeted geoengineering as a meaningful contribution to mitigate climate change' (p. 8). Positive impacts on some ice-dependent Arctic species and indigenous cultures are plausible.

Pleistocene park

This idea is designed to slow the thawing of the Arctic permafrost (Macias-Fauria et al., 2020; Zimov et al., 2009, 2012). The method is to introduce large herbivores into the permafrost region which would: (1) smash down trees, eat the young shrub and tree shoots, increasing winter and spring albedo; (2) trample the snow pack increasing its density and lowering its insulating capacity in winter thereby cooling the permafrost; and (3) increase the carbon storage capacity of the vegetation layer by fertilizing grasses, removing moss cover and improving surface drainage. There is a pilot scheme in East Siberia where 2,000 hectares of land has been fenced and stocked with bison, musk ox, reindeer and much of the taiga removed (https://pleistocenepark.ru). Measurements of snow cover properties, permafrost soil temperatures and carbon storage have been done for many years to establish how the herbivores affect the permafrost. These measurements confirm that the ideas are sound – herbivores keep down vegetation, albedo is raised, permafrost temperatures are lowered.

The scalability of the approach has not been demonstrated, and would require millions of square kilometres to be controlled. It is not clear if the simple introduction of herbivores would lead to conversion of taiga woodland to grass rangelands. It may be that human intervention is required to remove the tree cover, which would create problems in energy usage and environmental impacts. One thing in its favour is that historical ecological investigations of land use show that the vegetation cover is long affected by herbivore usage, sometimes for hundreds of years after the usage ends (Egelkraut et al., 2018). The alteration of the environment would also have vivid consequences for indigenous ways of life, though certainly less than the collapse of the permafrost would, or the urbanization and exploitation of the Arctic by oil and mining interests. One of the motivating factors behind the Pleistocene Park is that humans made an intervention in the early and mid-Holocene by hunting to extinction the large mammals in the Eurasian Arctic, thus ending the hitherto thriving and highly productive ecosystem, 'the Arctic savanna'. Hence, a Pleistocene Park intervention might be a return to a more 'natural state' than the present-day low productivity mire and taiga landscape, but landscapes have changed because of natural, as well anthropogenic factors. To do this kind of intervention requires scaling with no leverage – changing a landscape has few obvious feedbacks working in its favour and must take considerable time given the relatively slow reproduction rate of large herbivores.

Ice sheet conservation

These are ideas to limit sea level rise from the ice sheets, and fall into two categories. One type seeks to directly compensate for sea level rise by pumping excess water onto the surface of the slow-flowing accumulation zones of the ice sheets where it will freeze in the winter (Feldmann et al., 2019). While this approach has the advantage of directly mitigating sea level rise by removing water from the ocean, it has the disadvantage of working with one of the least sensitive 'control knobs' in ice sheet dynamics: as the ice thickens it tends to flow faster, leading to more ice discharge into the ocean, thus producing a self-limiting feedback. However, the increase in discharge takes several centuries to develop, and in the short term there is a direct correspondence between mass added to the ice sheet and mass removed from the ocean. There are two ways to increase the amount of ice on the Antarctic surface: pour on water and wait for it to freeze, or use snow cannons. Pouring water out onto the surface in winter creates ponds of bare refrozen ice that have a lower albedo than the surrounding snow surface; if the summertime air temperatures are high enough, this would lead to melting, especially if the water was not desalinated first. In addition, ponds of liquid water at the ice surface may drain to the bed, potentially leading to an increase in basal lubrication and accelerating ice flow towards the ocean. Using snow cannons instead of simple pouring would mitigate both of these problems but would probably require that the seawater be desalinated first. The energy required for desalination is roughly comparable to the energy required to lift the water to the right elevation against gravity, and those energy requirements are already a significant fraction of present-day global energy use (Feldmann et al., 2019). However, it may be possible using 12,000 high efficiency wind turbines, to generate that energy locally from the vigorous Antarctic winds. This does seem to be an entirely implausible use of resources, but it is not the only option for conserving the ice sheets.

The second group of ideas rely on slowing sea level by limiting the outlet glaciers that are the focal points of the instability that threatens parts of West Antarctica (Moore et al., 2018; Wolovick and Moore, 2018). While these methods do not directly remove water from the ocean, they rely on the leverage provided by sensitive ice dynamic feedbacks to multiply the effectiveness of smaller interventions. Important fast-flowing ice streams in West Antarctica are 50–100 km wide, while the critical outlet glaciers in Greenland are less than 10 km wide. Thus, targeted interventions at these strategic locations have the potential to achieve wide-ranging effects on the entire ice sheet catchment without requiring continent-wide infrastructure.

There are three approaches that target fast-flowing outlet glaciers: (1) preservation of floating ice shelves by building walls or positioning curtains to block off access to salty, warm deep currents; (2) building extra buttressing points that ice shelves can ground on and stabilize the inland ice; (3) slowing the outlet glaciers on land where they slide rapidly over sediments by drying the sediments, removing the lubrication at their beds and slowing the glaciers (Moore et al., 2018; Wolovick and Moore, 2018; Hunt and Byers, 2019). All three of these make use of feedbacks that would help to stabilize the ice sheet, for example, reduced access from warm currents means the ice shelves thicken and ground more readily on the sea floor, increasing buttressing. In addition, the natural variability in glacier size between Greenland and Antarctica provides an opportunity to sequentially advance from smaller glaciers to more difficult interventions at larger glaciers. After laboratory and computer simulations – which are already underway – the first step would be a small outlet glacier in Greenland, and then to the more important glaciers there: Jakobshavn, Helhiem and Petermann glaciers in ascending order of fjord width (Hunt and Byers, 2019). Lessons learned from Greenlandic glaciers could then be applied to the more difficult glaciers in Antarctica, such as the Totten, Pine Island, and Thwaites Glaciers.

There is no immediate urgency to implement these engineering feats, but now is the time to discuss researching them. The amount of research, development, and site exploration required to responsibly implement such schemes would likely take decades to complete. For example, at present there are only a handful of automated submersible vehicles that can operate in the ice shelf cavities. Since these are thousands of square km in area and hundreds of metres deep, probably a hundred times more vehicles are needed to map the sea floor at similar resolution as we know the upper surface of the ice sheets. Water pumping onto the outlet glaciers to increase their thickness and help them to ground on local sea bed highs might also be tested at the same time as these gradual increasing engineering challenges, or indeed other approaches that we have not yet thought of.

As with solar geoengineering, the first steps in the utilization of these techniques must come from computer simulation and laboratory work. There seem no obvious ethical or governance issues associated with this 'indoor' research. The following steps would need to be outdoors, and Greenland is the obvious place to begin.

3. How do targeted interventions compare with solar geoengineering?

In stark contrast to adaptation, both targeted and solar geoengineering address problems at source in globally equitable ways that could benefit rich and poor alike. Termination risk is smaller in the case of targeted geoengineering, when compared with solar geoengineering. Since glacier geoengineering and Pleistocene Park ideas are passive with no 'moving parts', they would require maintenance but be much less susceptible to sudden termination than, for example, stratospheric aerosol injection. This also means that they are less onerous for future generations. Sea ice preservation would require more frequent or on-going effort to maintain given the low inertia of the system. The moral hazard argument, which is used against solar geoengineering, is far reduced when it comes to targeted geoengineering: no one is proposing these as total fixes for climate, although solar geoengineering is not presented like that either. But conserving the ice sheets or permafrost is plainly not addressing global temperature rises.

Both sea ice management and permafrost re-wilding as described here provide no 'leverage' and would be vastly more expensive than solar geoengineering which has been costed at less than $5 B/yr (Smith and Wagner, 2018). The economics may change for permafrost management as increases in the price of carbon sequestered into a steppe grassland landscape could greatly reduce effective costs (Macias-Fauria et al., 2020). Localized solar geoengineering approaches such as marine cloud brightening targeted to cool the Great Barrier reef involve changing local climate, which via teleconnections, would have far-ranging consequences on climate elsewhere, potentially introducing legal and governance issues beyond the boundaries of the nation-state that initiated such measures. Targeted approaches seek to maintain the status quo, but environmental impacts of land management may be severe, especially in populated regions, but less in Antarctica and sea ice zones. They may be difficult to achieve politically, possibly even compared with solar geoengineering which has had considerably more evaluation of unintended impacts than any of the targeted interventions. Ice sheet conservation appears the most promising of the interventions we present. Despite the relative unattractiveness of both sea ice management and permafrost re-wilding in terms of impact on global climate, they may have a role in specific local instances. Perhaps where large carbon releases are likely to occur with modest temperature rises, or because of a significant cultural value to particular parts of its range. They may also be useful in contexts of ecosystem services by maintaining environments that are highly valued for human or ecological reasons.

4. The precautionary approach

We now turn to the governance regimes that might be relevant to the targeted interventions discussed so far. Principle 15 of the Rio Declaration on Environment and Development, (1992) states '[i]n order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation'. The precautionary approach, we think, is the most relevant over-arching governance principle. It is part of contemporary customary international law and has been incorporated into many international agreements and conventions and has been argued to be the most important – and perhaps the most controversial – development in international environmental law in the last decades (Wiener, 2007).

5. Governance of the permafrost

Much of the Arctic permafrost is located in just three countries: Canada, USA and Russia. It has sometimes been argued that one difficulty with solar geoengineering governance is that northern countries, particularly Russia, may wish to have a somewhat warmer temperature than many more southern countries would find best (Ricke et al., 2010). This argument relies on ideas that agricultural and silvicultural production in those countries would benefit from warmer summers, allowing the farming belt to move northwards or the forest growth to accelerate. However, this suggestion seems to neglect permafrost stability and thaw, which as stated earlier, would eventually release vast quantities of greenhouse gases that would undermine any global attempts at mitigating anthropogenic emissions. The upper 3m of permafrost contains twice the carbon than in the present atmosphere, but its release rate is uncertain in models (Chen et al., 2020) and highly dependent on rapid thaw (thermokarst) processes (Turetsky et al., 2020), which are not incorporated well into Earth System Models at present. Turetsky et al. (2020) estimate that although thermokarst might only occur in 1/5 of the permafrost area, it would dominate overall carbon losses. So there is a risk (which might be small), that the permafrost carbon feedback with radiative forcing could be larger than what solar geoengineering could control without extremely damaging side effects. Hence it may be easier to find a common global temperature point than earlier assumed.

Russia permafrost preservation attempts have focused on the Pleistocene Park. Bison and other large herbivores have been introduced to a fenced enclosure that has also been partially denuded of tree cover. Expanding this concept domestically in Russia would require purely domestic legislation, and would presumably meet with objections from local land owners, and reindeer herding groups who would understandably fear for their way of life and heritage. Those peoples are already being threatened by encroaching oil and mining interests, for example, gas pipelines have cut across traditional reindeer migration paths, new roads have brought invasive species as seeds inadvertently carried on vehicles that often out-complete endemic populations.

Much of Arctic Canada is in the three territories, Yukon, Northwestern Territories, and Nunavut, and taken together, indigenous peoples form the majority of their sparse population. The process of devolution has seen more autonomy transferred from the central government to the territories, though they have less power than Canadian provinces. However, co-management schemes are commonly used; hence, for practical purposes the First Nations and the Canadian government would decide together on targeted permafrost geoengineering regulations.

Alaska hosts most of the US permafrost. While its area and carbon storage is much smaller than Canada and Russia, the region has been warming rapidly. Thawing permafrost is an infrastructure issue – affecting buildings, food security, and especially the trans-Alaska pipeline carrying oil from the Arctic Ocean across the whole state to Valdez. The state is wealthy due to the oil, and thus both partially responsible for rising global temperatures, and also feeling their effects. In surveys (Carr and Yung, 2018), Alaskans showed reluctant acceptance for solar geoengineering which was feared to be an excuse for not mitigating, and to be another example of Western science and technology as vehicles of exploitation.

6. Governance of the arctic sea ice

The United Nations Convention on the Law of the Sea (UNCLOS, 1998) is the relevant international treaty providing regulations on the high seas. All states have freedom to navigate and exploit the resources in the water column in the high seas under the existing customary and treaty law (e.g. fisheries treaties, Law of the Sea broad provisions) provided that they pay due regard for the interests of other states in their exercise of the freedom of the high seas (article 87.2, UNCLOS). Before the Arctic Fisheries Agreement was signed in 2018 there were concerns that declining sea ice extent in summer could lead to unregulated and potentially highly risky fishing in high seas of the Arctic Ocean. Article 60 of UNCLOS specifies the rights of states to construct artificial islands, installations and structures in the exclusive economic zone. Article 87 of UNCLOS could serve as a similar legal basis for the high seas. In either case the rights of other states, for example the freedom of navigation, would have to be respected, which also follows from Articles 238 and 240 of UNCLOS. A small Ice911 installation would probably be justifiable on this basis, as long as it did not interfere with large regions of navigable waterways or in other ways impede the exercise of the rights of others under UNCLOS or harm the marine environment itself (article 240.(c) and (d), UNCLOS).

There may be important economic advantages in declining, or even absent summer sea ice – access to fossil fuel reserves, transit along the Northern Sea Route and the Northwest Passage, fishing and tourist access. The interventions would be on the marginal ice regions, perhaps in Beaufort Gyre. Thus, potentially directly affecting the Northwest Passage, and as the newly restored ice drifts, possibly other navigation routes as well. Hence, attempts to maintain the Arctic sea ice could be actively resisted, or at least its legality questioned, to minimize costs of altering shipping routes. The recent reports by the Arctic Council (AMAP, 2017a, 2017b, 2018) on climate change adaptation in three regions (Barents, Bering-Chukchi-Beaufort and Baffin Bay/Davis Strait) highlight that there is not just one way in which the Arctic suffers or benefits from climate change or can and should adapt to it. Hence a single Arctic view on geoengineering is not easily defined and should not be assumed.

The Arctic Council might be expected to be the premier body responsible for coordinating the eight Arctic states relations in the Arctic Ocean. But the Arctic Council is not a true international organization with rule-making power. All decision-making is done on a consensus basis, and treaties negotiated in the Council are enacted between the Arctic States without reference to the Council as a legal entity.

The Arctic Council was undermined in 2008 when the five Arctic coastal states (United States, Russia, Canada, Norway and Denmark – which represents Greenland in foreign affairs), that is excluding the three Arctic states lacking access to the Arctic Ocean, made the Ilulissat Declaration. The five Arctic coastline states emphasized their unique position and asserted their role as stewards of the Ocean. The five states rejected any proposals for Arctic governance supported by a legally binding agreement and declared 'no need to develop a new comprehensive international legal regime to govern the Arctic Ocean'. The meeting and declaration were controversial as they failed to follow the practice of the Arctic Council to invite representatives of indigenous peoples, and also because of its very limited membership.

Duyck (2011) lists many examples of the implementation of the precautionary approach by the Arctic states. For example, a temporary US moratorium on deep sea drilling in the aftermath of the Deepwater Horizon disaster. In Canada, the precautionary approach is one of the three principles of the country's ocean strategy. Paragraph 30 of the 1996 Canada Ocean Act contains a definition of the approach as 'erring on the side of caution'. The approach is part of the Canadian Sustainable Fisheries Framework. Several domestic laws and policies of coastal nations and regional environmental agreements also contain references to the precautionary approach. The recent Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean, 2018, which was agreed between the five Arctic coastline states, the EU, China, Korea, Iceland and Japan has been celebrated as the most precautionary fisheries agreement ever (Schatz et al., 2019). Additionally, the Fur Seal Convention and the Polar Bear Agreement, the North Atlantic Salmon Conservation Organization, The Convention for the Protection of the Marine Environment of the North-East Atlantic, and the Convention on the Future Multilateral Cooperation in North-East Atlantic Fisheries also contain direct references to the precautionary approach.

7. Governance of the Greenland ice sheet

The US offered to buy Greenland from Denmark after the Second World War, and again in 2019. The response from all political parties in Denmark was that: (1) Greenland was not for sale; and (2) it was not Denmark's to sell but a matter for the Greenlanders. In turn, the reaction of the Greenlandic government was that they were not to be bought and sold, and that Greenland was self-determining.

The relevance of this to targeted geoengineering is that it clarifies how Denmark sees the rights of Greenlanders to self-determination. So, the people who would have the rights and responsibilities for conserving the ice sheet, regulating engineering work, allocating permits, etc. would be the Greenland government. Assuming that the rest of the world is willing to pay to limit sea level rise, this suggests that the ice sheet could be monetized and valued as an economic resource for the local inhabitants. This approach would be close to the Payments for Ecosystem Services (PES) approach that has been utilized, for instance, in Finnish Lapland, where tourism entrepreneurs have paid Metsähallitus (the Finnish national parks and state-owned lands forestry administration) for postponing logging in forests with amenity values. Broader descriptions of the case, including criticisms of the concept are discussed by Sarkki (2011); and Naskali (2015) analyses the compatibility of ecosystem services thinking with neoclassical economics.

Steps for future governance

Since the matter of doing glacier geoengineering in Greenland is a purely Greenlandic decision, the framing of the issue to Greenlanders is important. There is a vast difference between presenting schemes as preserving their ice sheet, and building dams in fjords for the benefit of the rich West. One main result of self-determination has been a desire to promote domestic growth and employment by selling mineral and mining rights to the ice-free coastal regions. If an alternative way to monetize the natural resources they have, – the ice sheet itself, can be found, such as PES, it could present an attractive alternative income stream. However, the impacts of the potential ice sheet conservation on important livelihoods such as hunting, fishing and tourism, and on ecology and culture would also need to be evaluated. All research in Greenland requires research permits, with benefit to Greenland as one of the prerequisites.

Valuing the Greenland ice sheet and funding glacier engineering would have to be done by countries that felt sufficiently motivated to defend their own coastline infrastructure, and convinced enough of the science to understand the advantages of dealing with the problem at the source rather than locally. Such countries would also be interested in the larger sea level rise commitment from Antarctica and so understand that the Greenland work would be primarily about gaining experience before moving on to the bigger glaciers in the South.

8. Governance of the Antarctic ice sheet

Signatories of the Antarctic Treaty in 1959 agreed to set aside national claims to parts of the Antarctic land and ocean south of 60°S. The Treaty acts 'in the interests of all humankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord'. Pursuant to Article 1, the treaty forbids *any measures of a military nature*, but not the presence of military personnel or equipment for the purposes of scientific research.

Currently there are 54 members, but only 29 have consultative (voting) status. Voting status is given to states that demonstrate a profound scientific interest in Antarctica. While some states (the Netherlands) have been awarded voting status without having an Antarctic research station, possession of a station is, in practice, almost a requirement. Hence it is a rather exclusive club, heavily biased towards wealthy nations with a history of imperial expansion. Despite this, the Antarctic Treaty constitutes a unique approach to third states, which has enabled the original signatory parties to maintain a prominent role while engendering confidence in the merits of the regime which they were designing within the wider international community (Duyck, 2011).

Under the Treaty, scientific evaluation of ice sheet collapse would be allowed – as it is already being done. Since the aim of glacier geoengineering would be conservation of the ice sheet against collapse it could be argued that such intervention is consistent with the aims of the Treaty. Various other agreements are associated with the Antarctic Treaty. The most relevant being: Agreed Measures for the Conservation of Antarctic Fauna and Flora (entered into force in 1982); The Convention for the Conservation of Antarctic Marine Living Resources (1982); and especially The Protocol on Environmental Protection to the Antarctic Treaty also known as the Madrid Protocol, and in force since 1998.

The Madrid Protocol (https://www.ats.aq/e/ep.htm) appears to be the most relevant and important in the case of engineering the ice sheet. The Madrid Protocol demands protection of the Antarctic environment along with dependent and associated ecosystems. It further says that the intrinsic value of Antarctica must be a fundamental consideration in the planning and conduct of all human activities in Antarctica. With this aim, all such activities are to be planned and conducted so as to limit adverse impacts on the Antarctic environment; and avoid:

- adverse effects on climate or weather patterns;
- significant adverse effects on air or water quality;
- significant changes in the atmospheric, terrestrial (including aquatic), glacial or marine environments;

- detrimental changes in the distribution, abundance or productivity of species or populations of species of fauna and flora;
- further jeopardy to endangered or threatened species; or
- degradation of, or substantial risk to, areas of biological, scientific, historic, aesthetic or wilderness significance.

The environmental principles in the Protocol also include requirements for prior assessment of the environmental impacts of all activities and regular and effective monitoring to assess predicted impacts and to detect unforeseen impacts. Article 25 of the Madrid Protocol specifies that a 3/4 majority of the present voting members is needed to approve any amendment, and the treaty will run until at least 2048.

The case of the drilling in Antarctic subglacial lakes exemplifies issues related to the implementation by individual states of the precautionary approach when conducting or authorizing research projects on the continent. The Scientific Committee on Antarctic Research (SCAR, inter-disciplinary committee of the International Council for Science) recognized possible dangers from drilling towards the subglacial lake environment. Russia went ahead with drilling into the ice above Lake Vostok because the potential benefit to scientific research counted for more than the potential risk from drilling into the unique ecosystem (Bastmeijer, 2003).

The Madrid Protocol states that 'adverse effects on climate or weather patterns' must be avoided. The objective of conserving the ice sheets would actively seek to maintain those patterns. Not doing glacier geoengineering and allowing the ice sheet to collapse would change the climate, atmospheric and ocean circulations. Similar changes in the glacial environment should also be avoided, and again this would be better served by preserving the ice sheets than allowing them to collapse.

In practice, the building of curtains to divert ocean currents, the boring of bedrock tunnels, or the building of pinning points underneath ice shelves would certainly produce environmental impacts. However, construction projects are routinely undertaken in Antarctica albeit at much smaller scales (e.g. when stations are constructed, or aircraft runways extended). Even research projects are subject to impact assessments.

On the issue of whether boreholes and tunnels would violate the Madrid Protocol it is clear that the tunnelling would not be a case of mining – no ore or mineral would be extracted and removed from the continent. Hence an environmental impact assessment seems to be the only issue – albeit a very sizeable one that would require consideration from all the Antarctic Treaty consultative parties.

One idea for building berms or closing submarine troughs was to use material locally dredged from the sea floor. Dredging has serious environmental impacts, and dredging the sea floor might be considered mining. The text of the protocol states '[A]ny activity relating to mineral resources, other than scientific research, shall be prohibited'. However, Hunt and Byers (2019) showed that using metal curtains rather than simple piles of aggregate would be around 50 times cheaper, even considering the fairly frequent replacement costs. These curtains would be manufactured outside Antarctica and shipped to the locations as needed after detailed engineering designs and surveys.

Would consultative parties to the Antarctic Treaty seek to deny ice sheet conservation?

One reason to consider engineering Antarctic ice streams is because it offers an equitable way of tackling rising seas along the whole global coastline. This aligns closely with the 1992 United Nations Framework Convention on Climate Change article 3.1: *common but differentiated responsibilities* (UNFCCC, 1992), which specifies that wealthy industrialized states need to do more than poor developing states for mitigation. Thus, it would benefit the nations that are least able to provide infrastructure to defend their own coastlines more than richer countries. The richer countries would have to spend significantly more money to defend their coasts simply because more of it is developed, and that development is worth substantially more than developments in poorer countries. Not all rich countries have coastlines, but the 29 consultative parties of the Antarctic Treaty all do, and other rich nations would likely appreciate the importance of mitigating migration pressures caused by coastal flooding. Hence there seems to be a natural alignment of states to support ice sheet conservation rather than allowing it collapse and deal with the consequences individually.

Would states which are not parties or only non-consultative parties seek to become consultative parties, namely, voting members – for example, by building their own research stations – which may have glacier engineering as a focus? It is relatively inexpensive even for small countries to establish an Antarctic station on an easily accessible island – King George island on the Antarctic Peninsula is a popular choice for many states that wish to begin Antarctic research, with 10 different stations, all connected by roads and tracks, on an island only 95 km and 25 km across. If the Antarctic Treaty system becomes the primary governance body for glacial geoengineering, then there will be an incentive for low-lying nations to build small research bases in the most accessible parts of Antarctica in order to buy themselves a seat at the table. However, serious research on glacier engineering would probably require establishment of a station in the Amundsen Sea sector. Currently, there are no stations there, mainly because the region is beset by bad weather – it is the geographic centre of variability in the sea level pressure field, meaning that it sees more storms pass through than any other part of the continent. Hence, actually doing glacier geoengineering research is likely to be the preserve of the more established nations that are already deploying much infrastructure towards the mapping of the Amundsen Sea glaciers and their ocean environments.

Concluding remarks

In this article we have considered the possible governance implications and legal framework that targeted interventions in parts of the climate system – in particular the cryosphere – might have to work under. The ice sheets, sea ice and permafrost provide little direct economic benefit to nation states despite their importance for indigenous peoples. But they do provide extremely important features that enable the present climate to operate as humankind has grown used to.

Unlike solar geoengineering, where the whole global climate, or at least temperatures, are designed to remain closer to present-day values than under greenhouse gas forcing alone, targeted geoengineering seeks to mitigate particular effects of rising temperatures or help avoid certain tipping points in a targeted manner. Since it is rooted in preservation of the existing state rather than introducing new and undeniably controversial elements into the atmosphere, it likely presents easier governance challenges than does global, and even regional, solar geoengineering. However, as it does not seek to tackle the root causes of rising temperatures, or the other deleterious impacts of CO_2 (such as ocean acidification), it is not a complete solution to the climate crises. But then neither is solar geoengineering, which is largely seen as a way of avoiding temperature overshoot, preventing tipping points in the earth system that might occur along the path to a decarbonized future, or as the last resort, only to be deployed in utmost emergency, as some Arctic residents see it (H. J. Buck, I. Mettiäinen, D. G. MacMartin, and K. Ricke, Buck and Mettiainen 2019).

Corry (2016) makes the point that the Arctic should be considered as its own political sphere, and in that regard targeted conservation of these Arctic-specific systems seem to qualify, and lead to greater empowerment of the Arctic communities.

The University of the Arctic (motto: 'In the North, for the North, by the North') has about 150 members both from research and educational organizations mainly situated in the Arctic typically in remote towns. It provides on-line courses and a unifying structure that can be useful, in particular, for smaller institutes that are numerous in the Arctic. Hence it is a valuable resource in addressing directly the inhabitants of the Arctic, and hence developing and validating their own viewpoints (Corry, 2016). Arctic communities would benefit from recognizing the global value of their natural resources: permafrost, sea ice and ice sheets that they may not, as yet, be completely aware of. Hence this could raise the profiles of minorities that have historically been marginalized at the national level.

Because targeted interventions seek to ameliorate the damage to, or prevent the complete loss of, sensitive parts of the climate system, essentially by keeping them frozen, it ought to be well addressed by the precautionary approach, that is, a philosophy underpinning a regulatory framework designed to prevent harm to the environment. Many parts of the climate system are subject to strong long-term hysteresis, such that restoring them to their original state may be difficult or impossible if they are allowed to collapse. Thus, preventing their loss is a trans-generational opportunity to repay some of the damage caused by decades of greenhouse gas emissions. The fact that the poor countries, and the poorer citizens of those countries, would face the harshest consequences of coastal flooding, extreme weather, and carbon loss from permafrost propels the egalitarian argument for tackling the problems at source by mitigation or solar or targeted geoengineering, while they are still locked frozen rather than adapting to their melting. The governance of both the Antarctic and much of the Arctic Ocean is largely in the hands of the developed and relatively rich countries, and legally they should take prime responsibility, and proactively preserve the cryosphere.

Thus, we argue that these kinds of interventions are both legally and ethically justified.

Note

Very helpful referee and editor comments improved the manuscript. This research was funded by the National Basic Research Program of China (2016YFA0602701).

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supplementary Material

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