C2G
Carnegie Climate Governance Initiative

An initiative of
CARNEGIE COUNCIL for Ethics in International Affairs

EVIDENCE BRIEF

Climate-altering approaches and the Arctic

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Summary

This briefing summarises the latest evidence around Carbon Dioxide Removal (CDR), Solar Radiation Modification (SRM) and other climate-altering approaches and techniques relevant to the Arctic environment. It briefly describes a range of approaches currently under consideration and explores their relevance in the Arctic context. It also provides an overview of some generic governance issues and the key instruments relevant for the governance of different approaches.

The Carnegie Climate Governance Initiative (C2G) seeks to catalyse the creation of effective governance for climate-altering approaches, and in particular for SRM and CDR. C2G has no position on SRM or CDR research, nor whether any of the techniques should be tested or deployed.

This brief presents evidence relating to CDR and SRM approaches specifically as they relate to the Arctic environment. For more detail on the broader evidence relating to these approaches and their governance, please see the respective C2G evidence briefs on the governance of CDR and SRM which can be downloaded from the website at: https://www.c2g2.net/publications/

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Introduction

Now more than four years after the Paris Agreement on climate change entered into force, recognition is growing that without a rapid acceleration in action, limiting global average temperature rise to 1.5–2 degrees Celsius (°C) will not be possible. Progress towards achieving the Paris Agreement goals has been slow. Rather than fall, prior to the COVID-19 pandemic, emissions have only risen, hitting a new high of 55.3 billion tonnes of carbon dioxide (CO_2) equivalent in 2018 (UNEP, 2019). Even if all the Nationally Determined Contributions (NDCs) under the Paris Agreement were implemented, the Earth is still expected to warm by 3.0°C by the end of the century (range 3.0–3.5°C with 66% probability) (UNEP, 2020).

In this context, scientists have increasingly been exploring the additional use of large-scale interventions to limit climate impacts, including Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM). These climate-altering approaches are sometimes defined collectively as climate engineering or geoengineering.

This briefing focuses on climate-altering approaches that may be relevant to the Arctic, an important region to consider in the context of both its role in the climate system, and its importance in geo-politics. In section–I the techniques that could potentially be deployed in the Arctic, are briefly discussed and further detail on these techniques can be found in C2G's CDR, SRM and SAI Evidence Briefs (C2G, 2019, 2021 and 2021). A summary of other climate-altering techniques that would not be suitable for Arctic use is also provided.

There may be techniques that could be deployed in other regions that would have impacts on the Arctic environment, but these are outside the scope of this briefing. The briefing is not a detailed assessment of the techniques, rather it provides a brief description and analysis of each.

In Section–II on governance, a high-level overview of the relevant legal instruments, including existing law and some key non-binding principles, or codes of conduct are offered.

All the techniques discussed still require significant governance dialogue and decision making before they might even be considered for deployment at scale. C2G takes no position on the appropriateness of any of the techniques described herein. Rather, we seek only to broaden the conversation about them and catalyse the creation of effective governance for such techniques.

Background

Any discussion about the Arctic in relation to climate-altering approaches should consider the region not only as a location within which they may, or may not be deployed, but also in the context of its importance to the global climate system, to planetary and human wellbeing, and the region's geo-political importance.

Driven by various amplifying feedback mechanisms (Pithan and Mauritsen, 2014), the Intergovernmental Panel on Climate Change (IPCC) found that the rate of climate change in the Arctic is twice as fast as the rest of the Earth's climate (IPCC, 2018) whilst a more recent assessment by the Arctic Monitoring & Assessment Programme reported that it had warmed three times faster than the global average between 1979 and 2019 (AMAP, 2021). Some of the key environmental changes in the Arctic include:

- the Greenland ice sheet mass loss has increased six-fold since the 1980s (Mouginot et al., 2019);
- glacier melt is contributing 25–30% of observed sea-level rise (AMAP, 2017), and the smallest of Arctic glaciers are on a trajectory to completely melt by the end of the century (Radić, 2014);
- seasonal Arctic sea ice melt is on a trajectory such that the Arctic Ocean in summer may be mostly ice free by 2050 (Notz and Stroeve, 2018); and,
- permafrost thaw is accelerating, raising the possibility of the surface becoming a substantial source of methane and nitrous oxide emissions (Box et al., 2019).

Because more terrestrial methane may be released to the atmosphere sooner and more rapidly than previously thought (Yumashev et al., 2019) and the decline in reflective sea ice enables an amplifying feedback promoting ever higher temperatures (Yumashev et al., 2019), in 2019 the United Nations Environment Programme (UNEP) announced that a climate tipping point may have been reached in the Arctic and the Greenland ice sheet (UNEP, 2019). Such an acceleration in Arctic climate warming has the potential to affect the global climate (IPCC, 2018 and 2019).

Situating these climate considerations within the context of the Arctic's wider geopolitical position, described by the then United States (US) Secretary of State Mike Pompeo (2019) as 'being at the forefront of opportunity and abundance', suggests that future dialogue about any potential development, or deployment of climate-altering techniques in the region may be subject to important governance and geo-political debate (Corry, 2017).

Physically, the Arctic is a potentially useful location for some climate-altering techniques (NASEM, 2021). For example, the low population density and the availability of land and ocean surfaces offers considerable potential for albedo modification that uses manufactured reflective materials deployed on the surface (NASEM, 2021). Furthermore, the Arctic already stores carbon on a long-term basis. If these carbon stores were enhanced, they could provide additional storage for anthropogenic carbon over timescales that are not possible in the atmosphere (IPCC, 2014).

However, whilst there may be drivers that suggest the Arctic as an appropriate host for some climate-altering techniques, there are multiple other issues to consider. Some of the proposed techniques may perturb weather and climates elsewhere on the planet (Berdahl et al., 2014) and the placing of materials in the Arctic environment, including the atmosphere, surface and oceans raise additional environmental, social and political governance issues (Jackson et al., 2015).

Driven by better understandings of the region's capacity to drive significant changes in the global climate, and because the region is warming, possibly increasing access to natural resources, the region is increasingly being constituted as a global governance object (Corry, 2017) and it has been suggested that approaches to governance in the Arctic based on territorial sovereignty alone are breaking down (Corry, 2017). As part of this process, the Arctic climate is becoming increasingly and differently imagined, e.g., by the US as 'One Arctic', as an Inuit space, or as a subject of global climate governance (Steinberg et al., 2015), and conceived as a geography rather than a group of state territories (Koivurova et al., 2019). This evolving governance situation may have multiple implications, for example, including a weakening of how local interests are served (Corry, 2017).

Climate-altering techniques, in the context of this evolving governance landscape, may contribute to such a shift towards a globalist view of the region and provide interested actors with an object, or tool, through which to exercise control (Corry, 2017). The techniques may, through their design and discussion – and even more if deployed at scale – become tools through which future governance orders and relationships between people, states, resources and the environment are constructed among Arctic region states and others (Corry, 2017). As such, who engages in experiments, model simulations and early governance exchanges about these techniques and how they are organised and mediated may have important implications for the prospects for Arctic climate interventions and wider global governance agendas not only about the climate but more broadly.

The Arctic retains a special place in the environmental awareness of many societies (Hamilton, 2008). Processes that intentionally interfere with the Arctic may therefore be met with hostility, including from citizens living remotely from the region and who have never visited it. See for example the Greenpeace 'Save the Arctic' campaign (2013). Resistance, coupled with important governance questions, such as: who would deploy, monitor, pay for and insure against harms of any interventions; how the wider climate might respond to Arctic based interventions; how those would be responded to; and, how might trade, food production and other resource extraction be affected create a challenging governance environment for climate-altering techniques in the Arctic.

Further, it must be acknowledged that Arctic states and other countries have divergent interests in relation to climate change's effects on the Arctic (Corry, 2107). It is by no means a given that all countries will agree on the urgency, need and perhaps even on the desirability of stopping the current environmental changes in the Arctic. There are states who view the melt as an opportunity, freeing up access to valuable resources, and some who see it as a catastrophe, irreparably harming a pristine, unique natural environment, and those who view it as both (Corry, 2017). Thus, for some, interventions to protect the Arctic environment would be unwelcome whilst others may see it as an opportunity. This injects important uncertainties into the governance agenda. It cannot be assumed that climate-altering techniques, such as those discussed in this brief, can be addressed separately from the wider, on-going geopolitical struggle over the Arctic as a region and its purpose (Gorkina, 2013)

Finally, the Arctic environment creates significant physical challenges for any considering researching or deploying climate-altering techniques in the region. The Arctic has little by way of infrastructure such as deep seaports and few support facilities like rescue services. There is only very limited access to ready supplies of energy, and there are large distances between settlements with services. The Arctic is an extreme environment within which to work with low temperatures for six-months per year and four months of complete darkness per year in many parts (north of 78o).

SECTION I:

ARCTIC RELEVANT CLIMATE-ALTERING TECHNIQUES

Carbon Dioxide Removal (CDR)

Introduction

CDR is defined by the Intergovernmental Panel on Climate Change (IPCC) as *'Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities' (p544, IPCC, 2018).*

CDR is also known as carbon removal or carbon drawdown. Negative Emissions Technologies (NETS) and Greenhouse Gas Removal (GGR) are terms that encompass CDR, but which also include other greenhouse gases (GHGs) such as methane. It should be noted that there are currently no well-developed methods for removal of non-CO_2 GHGs. CDR, if ever implemented at large scale is expected to have climate cooling effects. In such circumstances, they are described as climate-altering techniques, climate engineering or geoengineering.

The emission pathways in the IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018) all require the removal of CO_2 from the atmosphere using CDR, if warming is to be limited to 1.5°C. These scenarios indicate the need to remove up to 1,000 billion tonnes (Gigatonnes (Gt)) of CO_2 by the year 2100, demonstrating the necessity of rapid and unprecedented action. It is in this context that CDR options are increasingly being proposed (UNEP, 2020).

Several potential CDR techniques are not considered suitable for the Arctic (see table 2), with key constraints being the cold, lack of light in winter, the short growing season, the challenges of building and maintaining infrastructure in the region, and safety. Others are less constrained by these environmental factors. Those techniques that are considered more suited to the Arctic environment are summarised below with an overview provided in table 1.

It is important to note that even where CDR techniques may be suitable for use in the Arctic, it may well be more efficient, cheaper and less resource intensive to use CDR techniques in other regions. This is not to suggest CDR is not suitable in the Arctic, but to flag it may be more challenging.

Afforestation and reforestation

The pinciple

Forestation is the intentional planting of new trees (afforestation), or replanting where they have been cropped, died, or been removed by other means (reforestation). This planting results in a net uptake of CO_2 as the trees grow. However, once a tree or forest reaches maturity, the uptake of CO_2 slows (Houghton, 2013) and when a tree's life cycle is complete it decomposes, and CO_2 is returned to the atmosphere (Read, 2009). This release of CO_2 may be avoided through forest management, and the biomass stored in long-lived wood products, or with them being used for bioenergy or biochar. Following harvesting, new planting and subsequent forest regrowth, or natural revegetation allows for continuing CO_2 removal.

Whilst trees cannot grow in the high Arctic, forests and forestry are an important element of the peri-Arctic environment and economy, making this technique of interest to the low Arctic and sub-Arctic regions. Biophysical constraints present in the Arctic will also play important role in the capacity of afforestation in the region to remove carbon. For example, hours of daylight, temperature, soil quality, vulnerability to flood, drought, fire or disease and future effects of climate change may all effect growth and storage capacity (Popkin, 2019).

A recent modelling study of a range of European forest-management scenarios concluded that, because of the surface darkening and cloud cover changes created, any added forests would approximately eliminate their carbon-storage benefits (Luyssaert et al., 2018). In seasonally snow covered environments, such as the Arctic, afforestation may have a net surface heating effect (Arora and Montenegro, 2011) and thus it may then not be suitable. However, in the future, if warming continues and snow and ice melting takes place earlier in the season and/or less land is covered by snow and ice afforestation may become a more viable option (Arora and Montenegro, 2011).

Forestation's global carbon removal capacity is contested. Griscom et al., (2017) suggests the capacity ranges from between 3 to 18 $GtCO_2$ per year, with the variation dependent on assumptions about the land available for planting ranging from 350 to 1780 million hectares (MHa). Whilst earlier evidence which informs the IPCC estimate indicates a global capacity of 1 to 7 $GtCO_2$ per year by 2050 (IPCC, 2018). In a more conservative assessment Smith et al., (2015) estimate a maximum sequestration through forestation of 12 $GtCO_2$ per annum by the year 2100.

The technique and its readiness

Afforestation and reforestation are already widely practiced throughout the world.

The cost estimates for afforestation and reforestation have been assessed at between USD $15 and $30 per tonne of CO_2 (Smith, 2015) whilst the IPCC only provide abatement costs of USD $5 to $50 per tonne (IPCC, 2018), demonstrating the considerable uncertainty regarding potential costs.

Current research activity

A better understanding of the balance of effects of planting trees between their carbon sequestration and warming effects is required. For example, shading by trees, particularly in the Arctic latitudes and in mountains or dry regions, where dark leaved conifers predominate may have a net warming effect (Lundquist et al., 2013). More research on climate models is therefore required to better understand the full effects of changes to forestry cover (Winckler, 2019).

A better understanding of how to balance competing demands for land use, such as biomass and bio-fuel production, cropping and grazing with forestation whilst also protecting the culture and rights of indigenous peoples in the most equitable, economically viable and socially acceptable way is required (Florin, 2020).

Socio-political considerations

Afforestation is broadly welcomed in many European states, whilst in other countries it remains a contested space (RS/RAE, 2018; NAS, 2015). Further, forestation may, in some circumstances, create concerns about the rights of vulnerable and indigenous people. Planting may undermine capacity for landowners to generate income in the short term, meaning they will want certainty regarding any payments that may be forthcoming to bridge the period between planting and harvest.

Governance

The monitoring of rates of both afforestation and deforestation needs to be improved and a precise global accounting system agreed upon (IPCC, 2018). Undertaking this work in Arctic regions, many of which are inaccessible, may be challenging.

Artificial ocean downwelling

The principle

Theoretical engineering interventions would transport cold surface waters saturated in CO_2 into the deep ocean (Zhou and Flynn, 2015, RS/RAE, 2018). At the surface, these 'down welled' waters would be replaced laterally by warmer surface waters. These would subsequently cool, taking up CO_2 because of enhanced solubility.

The technique and its readiness

At the time of writing, no artificial downwelling ideas have been tested. Nor are any technologies available capable of creating oceanic downwelling at very larges scales.

Current research activity

The technique is not currently being researched in any detail.

Socio-political considerations

Socio-political considerations have not been explored in the literature.

Governance

How downwelling might be governed is uncertain; however, it would likely be under the scope of the London Protocol and United Nations Convention on the Law of the Sea (UNCLOS).

Biochar production and deposition

The principle

Biochar, if stored in soil for long periods can provide not only a carbon store, but can also improve soil quality and crop yields (Lehmann, 2015), as well as water quality and nutrient levels (Smith, 2016).

Biochar is formed, in pyrolysis, when biomass is heated in a closed container, with little or no available air. In combination with sustainable biomass production, it can be carbon negative.

It is suggested that a tonne of biochar can remove between 2.1 to 4.8 tCO_2 (Lehmann, 2015, Hammond, 2011). Looking at the full literature range, the IPCC identify that the global potential of biochar in 2050 lies between 0.3 and 35 $GtCO_2\ yr^{-1}$ (IPCC, 2018). Woolf et al., (2010) estimate that the costs of biochar production ranges from USD \$18 to \$166 per tCO_2 produced.

Whilst the boreal forest may provide a significant biomass source, its use in the Arctic may be less effective than elsewhere. Critically, the application of biochar can lower surface albedo. During snow free seasons this may create some warming, which could partially counteract any climate mitigation benefits (Meyer et al., 2012). Further, the warming presence of dark biochar on the surface may delay the onset of seasonally permanent snow and ice cover, cover that has important albedo effects (Meyer et al., 2012).

The technique and its readiness

Biochar is a well understood and established method although it is not yet widely applied globally.

Current research activities

There is a wide range of on-going biochar research activity. Areas of current research include exploring uncertainties associated with decomposition rates of the various types of biochar, depending upon the pyrolysis feedstock and temperature (Anderson, 2020).

Within the Arctic context as elsewhere, more evidence is required to better understand the albedo effects (Yang, 2018) and which, if any feedstock might be most suitable for Arctic growing conditions.

Socio-political considerations

There are not expected to be major social concerns with the deployment and scale up of biochar, although there may be some social reticence and concerns about any effects on forests or food supply (Smith, 2010).

Governance

The monitoring, reporting and verification (MRV) of the take up and use of biochar can be difficult, both at the state and international level. Improved accounting will, though, be important in the future for carbon accounting purposes and it is possible that biochar will, in the longer term, become subject to international governance mechanisms such as the Convention on Biological Diversity (CBD) and United Nations Framework Convention on Climate Change (UNFCCC) (Vivid economics, 2019).

Building with biomass

The principle

This technique would harvest plants and trees for use in construction. The harvested materials could be used in a wide range of purposes within the building process. The approach has the potential to sequester carbon for between several decades and several hundred years and McLaren (2012) has suggested between 0.5 and 1 GtCO_2 per annum could be sequestered.

The technique and its readiness

Building with timber and other natural plant-based materials has been practiced for millennia and is a popular technique in the Arctic region. However, novel thermal and chemical treatments are increasingly available for use on fast growing soft woods to enhance their strength and duration (RA/RAE, 2018) meaning fewer slow growing trees, characteristic of the Arctic region may be required for future use in construction.

Current research activities

Building research is undertaken globally, within state funded and independent building research institutions, corporations, and universities.

Socio-political considerations

Whilst there may be some caution about the use of wood in construction, in relation to fire hazard and durability, its use is common-place in many states, including; the US, Scandinavia and the United Kingdom (UK), and it is suggested that there is unlikely to be any significant public reticence to overcome when seeking to expand the use of the materials in construction (RS/RAE, 2018).

Governance

If timber and plant material for building is imported or exported, an international agreement about who can claim the carbon credit arising from the activity will be required, along with a mechanism to monitor the flow of materials, and the carbon storage (RS/RAE, 2018).

National and supra national building regulations may constrain the use of materials in some circumstances (RA/RAE, 2018).

Carbon sequestration in soils

The principle

There are several ways that carbon can be sequestrated in soil (RA/RAE, 2018). These included:

- improved crop varieties and changes in their rotation and cropping;
- the use of novel biotechnologies;
- managing nutrients and optimising fertiliser use though careful timing and precise applications;
- minimising tillage and maximising the retention of organic material;
- improving grasses, especially by promoting and planting those with deep roots, and grass density; and,
- improving grazing management, paying attention to feed sourcing/production and stock density.

Whilst carbon sequestration in soils may be deployed within the Arctic, there are limitations on its value. Firstly, access to appropriate soils is limited, and, further, much of the ground is uncultivated and some is permanently inaccessible due to ice or snow cover.

The Technique and its readiness

There are no significant technical barriers to taking measures to improve soil carbon sequestration, and the practices are understood and in some cases already in practice in farming (RS/RAE, 2018). The global capacity to sequester carbon is estimated to be from 1 to 11 $GtCO_2$ per annum (Lal, 2011, Lal, 2013, Minasny, 2017).

In the longer term the capacity to store additional carbon year on year will decline as soils become saturated (IPCC, 2014, 2018), after which it becomes impossible to sequester additional carbon through these types of intervention.

There are no Arctic specific removals capacity data nor cost assessments for this technique. However, Smith (2016) suggests taking forward the required practices has the potential to create profit of up to USD $3 per tonne of CO_2 through improved productivity. In other circumstances, dependent on soil and environmental conditions, Smith suggests deployment may cost up to $12 per tonne.

Current research activities

Rapid and reliable methods are needed for the measurement of soil carbon and gas fluxes (RS/RAE, 2018).

Socio-political considerations

There is a lack of knowledge about the benefits of the approach, which will need to be overcome with education and training, if deployment is to be scaled up (Minasny, 2017).

Governance

Given the broadly positive effects on crop productivity and biodiversity, and the apparent lack of potential harms, governance of this method will likely be constrained to practical issues (Smith, 2012).

Direct Air Carbon Dioxide Capture & Storage (DACCS)

The principle

DACCS uses chemical engineering to separate CO_2 and other GHGs (then often referred to as Direct Air Capture and Storage (DACS)) from ambient air (the atmosphere around us) and store or use the sequestered gases in ways that will not contribute to global warming.

The removed gas is stored, for example, in geologic storage. Alternatively, it may be transformed into useable products such as fuels, however, any emissions resulting from the use of those fuels would then also need to be captured if the process is to result in net CO_2 removal.

The technique and its readiness

To extract CO_2, two approaches are used: adsorption and absorption. The first, adsorption uses solids to capture CO_2 whilst the second, absorption uses liquids.

Currently DACCS technologies are situated between the pilot plant stage and small scale or prototype demonstration in the field. Viebahan et al., (2019), suggests that DACCS is unlikely to be commercially available on a large-scale before 2030.

It should be noted that DACCS is expected to be more efficient in dry air (Wang et al., 2013) such as that experienced in the Arctic. However, a demand for water as part of the process suggests locating plants in arid deserts such as the Arctic may not be suitable.

Before the technologies can be scaled up, some outstanding issues, including energy requirements, the longevity of CO_2 storage, and the natural resource requirements, require resolution (NAS, 2015, RS/RAE, 2018). It is suggested that, in the long term, DACCS has a global sequestration potential of between 0.5 and 5 $GtCO_2$ per annum by 2050 (Fuss et al., 2018)

The availability of geothermal energy in the Arctic could be a potential source of power for DACCS (RA/RAE, 2918), suggesting, when combined with the dry air in which DACCS is more efficient (Wang et al., 2013) the Arctic maybe a suitable location for DACCS. Whilst there is underutilised hydroelectricity potential in Greenland, a demand for water as part of the process suggests locating plants in some parts of the Arctic may not be suitable if the availability of water from snow and ice requires additional energy to extract and melt the required water.

Estimates of financial costs of DACCS range from USD $20 to $1,000 per tonne of CO_2 captured (Sanz-Pérez et al., 2016 and (IPCC, 2018)).

Current research activities

Currently, the largest programmatic funding for GGR including DACCS is funded by UK Research and Innovation, which is committing USD $44 million to the topic of CDR over five-years, commencing 2021 (UKRI, 2019) whilst the X Prize Foundation offers $100m to solutions that can remove one ton of CO_2 per day and scale to gigaton levels.

Looking to the future research agenda, a number of studies have provided an overview of research gaps, or innovation 'needs' (Goeppert et al., 2012; Koytsoumpa et al., 2018; Sanz-Pérez et al., 2016; Sandalow et al., 2018; NAS,2019). A reading of these suggest the following are key areas of priority:

- achieving greater energy, heat and water efficiency;
- developing a better understanding of the sustainability impacts of DACCS;
- resolving remaining carbon cycle uncertainties;
- improving the production of synthetic renewable fuels using captured carbon;
- gaining a better understanding of how to deliver environmentally neutral secure, permanent carbon storage;
- the economics and policy of a DACCS compatible carbon market;
- the social acceptability of DACCS; and,
- global carbon accounting and governance.

Socio-political considerations

Blackstock and Low (2018) suggest that the social acceptability of DACCS cannot be assumed and evidence regarding the acceptability of DACCS is thin.

DACCS plants are likely to have a small physical footprint, compared to medium sized industrial facilities, and they would not be expected to create any threats regarding land availability, including to ecosystems services or food security (RS/RAE, 2018).

Governance

DACCS instillations will be situated within nation state boundaries and are not expected to cause direct environmental, economic, social and political transboundary harm requiring international governance.

Transparent MRV of achieved sequestration to monitor progress, and to provide accurate accounting of states' contributions and any carbon sequestration credits that may accrue (Zakkour, 2014). It is unclear how the international community might agree, set and stabilise, atmospheric carbon dioxide concentrations over the long-term.

Enhancing ocean alkalinity

The principle

Adding additional alkalinity to the surface of the ocean will result in an increased uptake of CO_2 by the ocean from the atmosphere. Enhancing alkalinity would help reduce the effects of ocean acidification on the marine ecosystem (GESAMP, 2019).

Deployment in the Arctic Ocean would be a likely 'hot spot' of unintended changes creating ocean biogeochemistry perturbations with unknown consequences (Gonzalez, 2017), suggesting the Arctic may not be the most appropriate location in which to attempt an enhancement of ocean alkalinity.

The technique and its readiness

No field trials have been undertaken, however, enhancing alkalinity would not require any novel or new technology (RS/RAE, 2018). These techniques can also be conducted on land (see Enhanced Terrestrial Weathering below), avoiding the costs of transport to and across the oceans.

The impacts of introducing particles from these materials into the oceanic environment are unknown suggesting further examination prior to implementation would be required (GESAMP, 2019).

The IPCC do not estimate a theoretical removals capacity for chemically enchancing alkalinity (IPCC, 2018) although theoretical studies have suggested that enhancing ocean alkalinity could remove as much as 3,500 $GtCO_2$ by 2100 (Gonzalez and Lilyina, 2016). Cost estimates range from USD $50 to $400 per tonne (GESAMP, 2019).

Current research activity

Currently, there is very limited research underway on the technique (Bach et al., 2019).

Socio-political considerations

Research by Corner et al. (2014) suggests publics may not be supportive of ocean-based interventions of this nature.

Governance

The technique could fall under Annex 4 of the London Convention and London Protocol and UNCLOS (Hubert, 2020). Other interested parties may include intergovernmental or civil society organisations (CSOs) and commercial interests related to chemical engineering.

Methane capture and processing

The principle

Ocean warming may lead to large-scale releases of methane with consequent large effects on the global climate, in particular in the Arctic region (Shakhova et al., 2010, Whiteman et al., 2013). In addition, the release of methane from thawing permafrost is also expected to accelerate global warming (Yumashev et al., 2019). Hence, there may be a need for methane capture.

The technique and its readiness

We find very limited information about methane capture. Lockley (2012) and Stolaroff (2012) have suggested covering kilometre-sized areas with plastic film and then either 'flaring off' captured methane or recovering it to storage. An alternative proposition to reduce the size of the methane bubbles forming at the seabed by sieving them through porous materials at the point of origin, causing them to dissolve into the water column before reaching the surface (Lockley, 2012). It has not been possible to estimate the potential scale of methane capture.

Current research activity

None, other than theorising about the method.

Socio-political considerations

Unknown.

Governance

It is uncertain how methane capture might be governed at this stage of its consideration.

Ocean carbon capture and storage (OCCS)

The principle

This technique would remove dissolved inorganic carbon from the oceans to be taken to long term storage sites, increasing the capacity of the oceans to absorb CO_2 from the atmosphere driven by a natural return to equilibrium.

The technique and its readiness

The principles underlying the technique are well understood and are used at small scale in laboratories during sea water analysis (Willauer et al., 2017). This technique would require scaling up, work on which is only at very early stages (GESAMP, 2019). Estimates of the theoretical maximum efficiency of this technique are uncertain given the limited understanding of how scaling up would work.

Current research activity

Technical and economic modelling is underway (Eisaman et al., 2018) exploring cost and infrastructure challenges of OCCS. However, many other critical research issues remain (GESAMP, 2019).

Socio-political considerations

It is unclear what incentives would be required to encourage up-take were a technology proven. Which institutions would develop this and why is unknown? It is also unknown where the captured carbon would be stored and at what opportunity cost, nor whether the technique would be socially acceptable.

Governance

If conducted in inshore waters, OCCS would be subject to nation state regulation, customary law and wider governance dialogue. In international waters, the governance frameworks are uncertain.

Ocean fertilisation with Iron (OFI)

The principle

Photosynthesis by plankton in the ocean removes around 40 $GtCO_2$ per year from the ocean surface and transports it downward to the deep ocean (RS/RAE, 2018). Iron ocean fertilisation seeks to enhance this process by introducing additional micronutrients to drive greater plankton growth.

The technique and its readiness

Distributing iron into the oceans is technically feasible and the industrial infrastructure required is well understood (GESAMP, 2019). The technique may be more pertinent to the Arctic than many other waters and modelling suggests that the subarctic Northern Pacific would be a particularly productive location within which to deploy the technique (Bopp et al., 2013).

Estimates for the capacity for ocean iron fertilisation to remove and store CO_2 are extremely uncertain. For example, the IPCC estimates a range of 15.2 Kilotonnes (kt) for small interventions to 44Gt, (IPCC, 2018) whilst the Royal Society and the Royal Academy of Engineering, adopts an estimate of 3.7 $GtCO_2$ per annum (RS/RAE, 2018). Cost estimates for this technique also vary. The IPCC, for example, estimate a cost range of between USD $2 and $457 per tonne of CO_2 removed (IPCC, 2018).

Some potential side-effects include population increases of toxic species of single-celled algae diatoms (Silver et al., 2010 and Trick et al., 2010). If iron fertilisation is carried out over large areas, there may be reductions as well as increases in productivity, affecting fisheries and potentially nutrient robbing from downstream regions, potentially with geopolitical and economic implications (GESAMP, 2019).

Current research activity

Ocean iron fertilisation is an area of active research interest and research assessment of carbon transfer in large-scale experiments is required (Williamson, 2016).

Socio-political considerations

The Haida Gwaii community off Prince Rupert Columbia in Canada became subject to global news in 2012 after the Haida Salmon Restoration Corporation had released 120 tonnes of iron sulphate into an ocean. It was flagged to the media (Lukacs, 2012). Contiguous with the Haida experiment the governing body of the London Protocol tasked its Ocean Fertilisation Working Group to develop options for providing a control and regulatory mechanism for ocean fertilisation following which the London Protocol was amended (LC&P, 2015) (see ‘governance’ below).

Research suggests that the public, at least in the UK, are broadly unaware of the technique, (Corner et al., 2014)

Governance

The technique falls under Annex 4 of the London Protocol (IMO 2013). Other interested parties could include civil society and commercial interests.

Ocean fertilisation with macro-nutrients, nitrogen and phosphorus (OFM)

The principle

The underlying principle of this technique is the same as for iron fertilisation (above), it simply uses different substances.

The technique and its readiness

Nitrogen and/or phosphorus would be added to nutrient-impoverished waters. It has been suggested that nitrogen fertilisation, when additional costs including manufacture, transport and distribution by vessels on the ocean are included, is potentially a more efficient means of sequestration than iron fertilisation (Harrison 2017 and Matear and Elliot 2004).

Harrison (2017) suggests that the technique has a theoretical capacity to offset up to 15% of annual global CO_2 emissions (as at 2017).

The Arctic Ocean's waters are not nutrient-impoverished meaning that this technique may not be best suited to the region and its deployment would likely be more efficient in the tropics and sub-tropical waters (GESAMP, 2019).

Current research activity

Research is still required to understand the viability of this approach.

Socio-political considerations

These are broadly the same as for iron fertilisation. However, phosphorus stocks are in decline, process are volatile and there are concerns regarding future capacity to fertilise crops. The geo-politics of phosphorus are also important, with large mines only in Morocco, Russia, China and the US (GESAMP, 2019).

Governance

The technique falls under Annex 4 of the London Protocol (Hubert, 2020). Other interested parties would include intergovernmental or CSOs, and commercial interests, especially those associated with food production and mining/minerals.

Restoring peatlands, wetlands and coastal habitats.

The technique and its readiness

The restoration of these environments requires little in the way of new technology (Zedler, 2005). It centres on rewetting or re-establishing environments, normally through practices to block excessive draining (SNH, 2019). Coupled with this, measures to protect the ecosystems against further exploitation and degradation are required (Bain, 2011).

Peatlands play an important role in Arctic and peri-Arctic regions, acting as a 'blanket' insulating permafrost and preventing it from thawing (Kopansky, 2020).

The release of methane and nitrous oxide from wetlands may release between 20% to 25% of global emissions (Whiting, 2001). Whilst reviews of methane mitigation technologies indicate that this may be a challenging task (Stolaroff, 2012, Lockley, 2012), it is known that such releases can be reduced significantly by planting of mosses and other plant coverage on non-coastal wetlands.

Current estimates of the maximum long-term carbon sequestration that can be achieved through improving wetlands, indicate a potential of between 0.4 and 18 tons of CO_2 per hectare per annum, scaling to a global potential of approximately 1 $GtCO_2$ per annum by 2030 (Bain, 2011).

Coastal ecosystem restoration could theoretically remove 0.2 $GtCO_2$ per annum (Griscom et al., 2017). However, this would be challenging, because of the semi-permanent and on-going nature of most coastal land-use change (Li et al., 2018). Carbon sequestration costs in freshwater wetlands have been estimated to be in the range of USD $10 to $100 per tCO_2 (Kayranli, 2010) and estimates for saltwater environment restoration range from USD $2,508 to $383,672 per hectare (Bayraktarov et al., 2016)

Current research activities

If wetland restoration is to be fully understood and any potential for CDR fully realised, more research is required.

Socio-political considerations

The key barriers to large-scale wetland restoration are largely financial (RS/RAE, 2018). Financial incentive mechanisms may then, be required, and, maintained over the long-term (Kayranli, 2009).

Challenges also remain regarding the MRV of achieved carbon sequestration, cost-effective monitoring of fluxes, and the effects, positive or negative, of land-use change (Kayranli, 2009, RS/RAE, 2018).

Restoring wetlands can have a range of, non-climate related benefits some of which may contribute to wider global sustainability goals (Zedler, 2005).

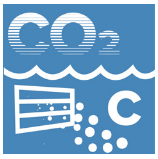
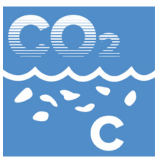
Governance

Interested parties in wetlands restoration would include:

- Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat (UNESCO, 1971);
- Convention on Biological Diversity (CBD);
- United Nations Framework Convention on Climate Change (UNFCCC);
- food and farming interests, such as the UN Food and Agriculture Organisation (FAO);
- coastal shipping interests; and,
- CSOs and landowners.

Table 1 Overview of Arctic relevant CDR Techniques

	TECHNIQUE	READINESS	ACTIVE RESEARCH AREA	GOVERNANCE FRAMEWORK	SOCIAL ACCEPTABILITY
Afforestation and Reforestation	Planting of forests and restoration of ecosystems that result in long-term storage of carbon.	Already widely practiced. Could be deployed at scale with little further development.	Yes. Exploring gas fluxes from trees, land use change effects and albedo changes.	The United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, Paris Agreement, the Food & Agricultural Organisation (FAO). Questions remain regarding social justice (i.e., land use issues). A requirement for better monitoring, reporting and verification (MRV) of achieved sequestration.	Competing demands for land use need governance. A lack of financial incentives to encourage afforestation.
Artificial Downwelling	Pumping oceanic waters to deep waters to enhance carbon uptake	Not currently practical, even in principle in engineering terms, to deliver cooling.	Very limited if any activity.	Unresolved.	Unknown.
Biochar Production and Deposition	Biomass burning under low-oxygen conditions (pyrolysis) creates "biochar", which is then added to the soil to enhance soil carbon.	A well-established technology with an evolving market. Only likely to be of limited value in the Arctic.	Yes, explorations of decomposition rates and the relationship with feedstock and temperature.	State and customary law, UNFCCC and FAO. Better MRV is required. A transboundary trade in biochar may require international agreement regarding carbon credit allocation.	No major social concerns.
Building with Biomass	Using carbon embedded in timber in construction.	Widely practiced.	Yes. Improving materials strength & combustion protection. Reusing materials during decommissioning.	Imported timber may, in the future, require international agreement re carbon credit allocation. Potential governance issues around land-use change.	No major social concerns. Some barriers in construction industry related to uptake.
Carbon Sequestration in Soils	Land management changes that increase soil's carbon concentration.	No significant barriers. Some have adopted the practice. Limited knowledge of the techniques in the agriculture community.	Yes. A better understanding of gas fluxes from enhanced soil is required.	The UNFCCC and Paris Agreement, the FAO and the 4p100 initiative. A requirement for better MRV of achieved sequestration.	No major social concerns.

	TECHNIQUE	READINESS	ACTIVE RESEARCH AREA	GOVERNANCE FRAMEWORK	SOCIAL ACCEPTABILITY
 Direct Air Capture with Carbon Storage (DACCS)	Chemical processes that separate CO_2 from air for subsequent storage.	No technical constraints to deployment aside from scale up and energy supply/use.	Yes. Demonstrator projects improving energy, heat and water efficiency, whole systems modelling to understand scale up.	With amendments may be relevant to UNFCCC, Kyoto Protocol and Paris Agreement.	It is uncertain how publics would respond to this technique.
 Enhancing Oceanic Alkalinity	Additional alkalinity in ocean surfaces will increase the uptake of CO_2.	A major challenge remains to reduce the large carbon/energy footprint of manufacturing processes.	Very limited.	Would be subject to United Nations Convention on the Law of the Sea (UNCLOS) and the London Protocol in the future, if named in annex 4. The Convention on Biological Diversity (CBD).	Limited research on broadly similar techniques suggest it is unlikely to be welcomed.
 Enhanced Terrestrial Weathering	Minerals added to the land surface which react with atmosphere and permanently remove carbon.	No technical constraints to deployment aside from scale up and infrastructure development.	Yes. Limited research underway.	Subject to nation state law. With amendments may be relevant to UNFCCC, Kyoto Protocol and Paris Agreement. With run-off, potentially the London Protocol.	Only limited evidence regarding how publics would respond to this technique.
 Methane Capture and Processing	Limited information about capture or storage techniques.	No available techniques.	None.	Unknown.	Unknown.
 Ocean Carbon Capture and Storage (OCSS)	The chemical removal of dissolved inorganic carbon which is taken to storage sites.	Principles well understood. Chemical engineering research is required before a viable technology becomes available for testing.	Mainly technical and economic modelling	If conducted in Exclusive Economic Zone (EEZ) waters, OCSS would be subject to nation state terms. On the high seas, the storage of CO_2 beneath the seabed would be covered by the London Protocol.	There is no evidence to indicate the nature and scale of any responses.
 Ocean Fertilisation with Iron	Placing iron in ocean surface water encourages plankton growth, which takes up CO_2 during growth.	Technically feasible and the industrial infrastructure required is well understood.	Yes. Environmental impacts and capacity to uptake CO_2 .	Research addressed under the London Protocol and UNCLOS. The CBD.	Limited research suggests it is not welcomed.

	TECHNIQUE	READINESS	ACTIVE RESEARCH AREA	GOVERNANCE FRAMEWORK	SOCIAL ACCEPTABILITY
Ocean Fertilisation with Macro-Nutrients, Nitrogen and Phosphorus	Placing nutrients in ocean surface water encourages plankton growth, which takes up CO_2 during growth.	Modelling studies only to date.	Very limited theoretical and modelling research.	Research addressed under the London Protocol. UNCLOS and the CBD.	May not be welcomed – see iron fertilisation.
Restoring or Creating Peatlands, Wetlands and Coastal Habitats.	Rewetting, reclaiming or creating new wetlands to enhance soil carbon levels.	Requires little new technology.	Yes. Reducing methane release and its capture.	The UNFCCC, Kyoto Protocol, Paris Agreement and FAO. Land use trade-offs. Better MRV.	A key barrier may be the lack of financial incentives to encourage land-use change.

Other approaches to CDR not considered suitable to Arctic use.

The Arctic environment creates conditions that would limit the capability of some CDR approaches to remove carbon efficiently or effectively, those techniques are summarised in Table 2. For a more detailed assessment of these techniques, see the C2G Evidence Brief: Carbon Dioxide Removal and its Governance.

Table 2. CDR techniques considered unsuitable for Arctic deployment

TECHNIQUE	BRIEF DESCRIPTION	INAPPROPRIATENESS FOR ARCTIC
Crop Residue Oceanic Carbon Sequestration	Ballasted bales of crop residue would be dumped into the deep ocean or off the deltas of large rivers.	Residues dumped in less than 1,000 metres (m) can have significant impacts on the ecosystem (GESAMP, 2019). The Arctic oceans mean depth is only 1039m (Ostenso, 2019).
Macroalgal Cultivation for Sequestration	The large-scale farming at sea of macroalgae to capture carbon through photosynthesis (N'Yeurt, 2012). The biomass would subsequently be harvested either for sequestration or bio-fuel production (Sondak et al., 2017).	Low light conditions under ice, and during the Arctic winter more widely constrain the growth of macro algae such that large scale farming would not be sufficiently productive (Hancke et al., 2018). Although there is evidence that kelp growth rates in ice free waters are accelerating with warming (Filbee-Dexter et al., 2019).

TECHNIQUE	BRIEF DESCRIPTION	INAPPROPRIATENESS FOR ARCTIC
 Artificial Upwelling in the Oceans	Artificial upwelling would bring deep, nutrient-rich waters up toward the surface stimulating phytoplankton growth and the absorption of carbon.	Across much of the mid and low latitude oceans, nutrients are depleted in the surface waters, limiting biological production (Moore et al., 2013); not the case in higher latitudes, meaning only minor potential gains.
 Bioenergy with Carbon Capture and Storage (BECCS)	Biomass is grown as feedstock and burnt to generate energy. Gasses released from combustion are captured at source and sequestered permanently (e.g., in geological formations) effectively taking the emissions out of the carbon cycle (Daggash et al., 2018).	BECCS requires a large and secure, regular supply of biomass, grown locally to minimise emissions from transport. Rapid growing, cropping and replacement is required. This is not possible at the scale required in the Arctic.
 Enhanced Terrestrial Weathering	Naturally occurring chemical reactions that absorb CO2 are enhanced by the spreading of ground materials (e.g., Olivine) on the substrate which react with water.	The technique requires that the land surface be exposed to the air (not covered in snow or ice) and liquid water to promote the chemical reaction (for more information see (RS/RAE, 2018). Dust from the ground up materials would blow onto ice and snow reducing its albedo and warming the ice.

Solar Radiation Modification (SRM)

Introduction

The underlying objective of SRM techniques is to increase the reflectivity, ('albedo'), of the Earth's surface or atmosphere. An increase in the amount of sunlight, known as solar radiation, returning to space would alter the Earth's radiation balance, working to shade and thus cool the surface, countering some of the greenhouse warming. Further detail can be found in C2G Evidence Briefs covering, Governing SRM and SAI and its Governance (see C2G, 2019b and C2G, 2021).

Estimates suggest that if SRM were deployed, it would need to reflect roughly 2% of sunlight back to space, to counter this amount of warming (Shepherd, 2009). However, SRM is not a substitute for emission reductions to net zero, and then net negative, as it does not address the underlying cause of global warming - increased atmospheric GHG concentrations (Robock, 2018). Given the complexity of the climate system, unintended consequences of deployment of SRM may occur if deployed at climate-altering scales (Russell et al., 2012, Robock, 2018).

Some SRM interventions may have an immediate direct cooling effect on local temperatures (Watts, 1997). Other SRM interventions may be capable of delivering planetary scale cooling within a time frame of a few years (Keith, 2013).

SRM presents complex technical, socio-political and governance challenges. This gives rise to governance questions including, how to measure potential effects on the global climate to questions such as 'who would decide to deploy SRM', 'how much cooling might be appropriate' and how would liability for (perceived) damages be dealt with and how might 'losers' be compensated? SRM also gives rise to questions of moral hazard, i.e., discussions about its potential use, or any future deployment may undermine individual, collective or political incentives and calculations for delivering mitigation (Lin, 2012). It has also been suggested that SRM could potentially give rise to security governance issues between countries (Chalecki and Ferrari, 2018), a topic further discussed in the C2G Evidence Brief: Governing Solar Radiation Modification (C2G, 2020).

Each of the main SRM techniques are presented in the following section and summarised in Table 3 at the end of the section.

Marine cloud brightening (MCB)

The principle

Clouds over the oceans would be engineered to be brighter, increasing the amount of sunlight reflected out into space, hence achieving cooling.

The technique and its readiness

In relatively aerosol-free parts of the atmosphere, such as over the Arctic and oceans, increasing the number of cloud-condensation nuclei (particles around which droplets of water coalesce to form clouds) would raise cloud (and planetary) albedo significantly and may also increase the cloud longevity (Albrecht, 1989). An MCB intervention would seek to increase the number of cloud-condensation nuclei by spraying fine particles into clouds. The most likely candidate base material is sea water.

The scale of effect of this technique could be very large (Latham et al., 2009). However, the potential to scale up MCB to the scales necessary for planetary cooling is unclear (Brent, 2020).

MCB could also be deployed locally, securing regional benefits and such interventions are currently being researched in Australia, exploring the use of MCB in Great Barrier Reef protection (BRF, 2018).

Modelling suggests MCB could be deployed within the Arctic region delivering a rapid cooling effect (Parkes, 2012), slowing ice melt and cooling the Earth more widely in due course (Nalam et al., 2017). However, such a deployment may also drive atmospheric heat from regions to the south of the Arctic into the Arctic region, counteracting some of the direct effects of the MCB deployment. Distribution mechanisms might be technically uncomplicated. It has, for example, been suggested that solar powered ships or remotely operated aircraft could routinely deliver the required particles at precisely the locations needed (Wood et al., 2018).

It is uncertain how the climate will respond to the large-scale radiative forcing MCB may have the capacity to deliver. Climate models suggest MCB could be very efficient in reducing global warming (Kravitz et al., 2014). However, risks could conceivably include changes to weather systems and important local climate phenomena such as monsoon rains and ecosystem functioning (Park et al., 2019, Keith et al., 2016, Mercado et al., 2009).

If an MCB deployment that had cooled the planet were terminated over a short time, a significant and rapid temperature 'bounce back' may result, whilst the climate re-stabilised (Kosgui, 2011). This rapid temperature increase, known as a 'termination shock', could be damaging (Robock, 2018) and has the potential for large-scale environmental, economic and social impacts (Matthews and Caldeira, 2007). However, is has been argued that there are no obvious scenarios under which rapid termination might be allowed to occur under a well-governed system (Parker and Irvine, 2018).

Current research activity

A key set of research agenda related to Arctic SRM is to develop a better understanding of how deployment in the Arctic might affect sea ice formation and the wider global climate. These are explored in more detail in the discussion of Stratospheric Aerosol Injection (SAI) SRM below.

In April 2020, the world's first ever outdoor SRM experiment was undertaken to test a delivery mechanism to spray nano-sized sea-salt particles into the air above the Great Barrier Reef (GBR).

Socio-political considerations

Public perceptions and likely responses to MCB are uncertain (Taylor, 2019). Research in the UK suggests that a perceived controllability of MCB may reduce citizens' concerns about governance of the technique (Bellamy et al., 2017).

Governance

Large scale MCB requires governance, not only because a decision to deploy would affect the Earth's climate, but also because it may affect other systems such as the oceans, weather, agriculture, regional hydrologic cycles, and biological productivity (Shepherd, 2009), affecting states and regions, both positively and negatively, and in different ways. Monitoring and verifying the effects of MCB deployment would also have governance connotations which are yet to be resolved.

Increasing ocean surface albedo

The principle

If the albedo of the ocean surface, or (floating) sea ice were enhanced the Earth's radiation balance would be changed (Shepherd, 2009). Limited competition for space on the oceans, compared to on land may mean that locating an intervention over the Arctic Ocean may be less politically challenging than on land (Moore, 2021).

The technique and its readiness

Several approaches to increasing ocean surface albedo and 'ice management' are discussed in the literature. Manufactured reflective floating silica spheres could be placed on sea ice to slow melting (Field et al., 2018) and micro bubbles might be deployed using a bubble injection technology (Seitz, 2011), a simulation of which suggests that a 0.05% increase in ocean albedo could potentially cool global average surface temperatures by 2.7˚C (Seitz, 2011). Alternatively, stable reflective rafts of foam could be spread on the surface (Aziz et al., 2014) and bright calcifying phytoplankton blooms have been shown to increase the reflectivity of the ocean surface (Holligan et al., 1993) and could be created using the iron fertilisation techniques discussed above.

An important characteristic of techniques to increase ocean surface albedo is the likelihood of them being able to deliver local or regional cooling, such as in the Arctic – reducing heat during local temperature spikes.

Currently, none of the proposed approaches described are available for scale deployment and they all give rise to important questions about the environmental impacts of introducing alien materials into the environment and changing large surfaces.

Current research activity

Work on developing spheres, bubbles, sea ice and foams are underway in small scale studies, including small scale field trials. For example, the Arctic Ice Project, a non-profit organisation based in California is testing and developing silicon dioxide microspheres for Arctic deployment (ICE911, 2019) and small-scale field trials in Canada and the US are underway (Field et al., 2018).

It is estimated that 25,000 kilometres square (km2) of the Arctic, the equivalent of 0.7% of late summer ice coverage, at its lowest extent to date, could be covered by the spheres at a materials-only cost of USD $300 million (Field et al., 2018). Future research questions for the Arctic Ice Project include how the spheres would respond and behave in the open ocean including how quickly they would disperse or sink. However, modelling of scale-up deployment of the Arctic Ice Project's method suggest that sea surface temperate reductions of -3˚C may be possible in the Barents and Kara seas (Field et al., 2018).

Remaining research challenges include improving the longevity of bubbles and foam and enhancing their resilience to disturbance and breakdown by wave, rain, tide and shipping (GESAMP, 2019). Environmental impact research should also be considered in parallel with technique research to better understand potential effects, risks and harms.

Socio-political considerations

There is no market to support deployment of techniques to increase ocean surface albedo. The extent to which deployments would be socially acceptable are uncertain. There is limited evidence whether community consent for deployment of microspheres such as those under development by the Arctic Ice Project is or will be problematic. However, one report (Jay, 2019) suggests deployment may not easily receive community consent.

Governance

The techniques discussed will likely be subject to regulation by the London Protocol as a type of marine SRM, as well as the UNCLOS if they were to locate beyond the EEZ. Other interested parties would include CSOs, Intergovernmental Organisations (IGOs), and commercial business interests.

Stratospheric Aerosol Injection (SAI)

The principle

SAI SRM seeks to increase the amount of reflective aerosol particles in the lower stratosphere increasing the reflection of sunlight back into space and cooling the planet (Keith, 2018). For more detail see C2G Evidence Brief on SAI Governance (C2G, 2021).

SAI would deploy aerosols in the lower stratosphere (Keith, 2013). It is expected that SAI could be capable of delivering planetary scale cooling within a year (Keith, 2013).

Evidence of the effects of stratospheric aerosols on the climate is available in the natural environment from volcanic eruptions. For example, in July 1991, the Mount Pinatubo eruption cooled the global climate by an average of 0.5˚C over the following two years (Dutton and Christy, 1993) before the aerosols rained out.

SAI would not address the cause of warming and it could carry, undermine individual, collective or political incentives for delivering mitigation (Lin, 2012).

The technique and its readiness

Three key factors drive interest in SAI; the potential rapidity with which it may take effect (Keith 2013), the high potential cooling efficiency and potential low direct cost of deployment (Keith, 2013). Because the particles would fall out of the stratosphere over time (estimates suggest between one and three years), they would need to be continually replaced to maintain the level of cooling (Keith 2013). Smith and Wagner (2018) suggest that developing a new aircraft, suitable for SAI work would neither be technologically difficult nor prohibitively expensive - cost estimates range from USD $1 to $3.4 billion (Bingaman et al., 2020, Smith and Wagner, 2018).

The theoretical relative ease of implementation, combined with the potential radiative efficiency of aerosols, suggests the direct costs of SAI might be low. A Royal Society review suggested SAI would be in the order of 1,000 times less expensive than other climate-altering techniques, although MacKerron (2014) has drawn attention to the importance of indirect economic costs meaning the hidden costs of policy and governance development, could be higher than the direct costs (Florin et al., 2020).

Whilst the costs of SAI may be low in comparison to other climate-altering techniques (Keith, 2013), because deployment scenarios assume SAI would be used in combination with CDR and emissions reductions, SAI costs would be an additional cost, on top of the costs of the chosen levels of CDR and emissions reductions (Keith, 2013, IPCC, 2014).

The choice of materials to use in the formation of the aerosols remains to be resolved and may pose important questions. For example, were sulphate, one candidate particle, used it may drive ozone loss Tilmes and Mills, 2014). Some potential SAI particles may, on the other hand, enhance ozone.

It is not yet clear in detail how the climate might respond to the large-scale forcing SAI. Modelling suggest that SAI could be very efficient in reducing global warming (Irvine and Keith, 2020). Further, it is suggested that SAI could reduce globally aggregated risks of climate change (Irvine et al., 2019). However, SAI may increase climate risks for some regions, including the Arctic (Irvine et al., 2019). Such risks could conceivably include changes to some weather systems including precipitation (Keith et al., 2016, Mercado et al., 2009).

As with MCB, if SAI had ever been deployed and was then terminated over a short time period, a significant and rapid temperature 'bounce back' may result, whilst the climate re-stabilised (Kosgui, 2011) increasing temperatures rapidly (Robock, 2018). Such a termination shock has the potential for large-scale environmental, economic and social effects (Matthews and Caldeira, 2007). Modelling of the Arctic's response to the cessation of aerosol injection after a 50-year programme of deployment, has suggested that the Arctic climate system would rebound quickly, and any sea ice or snow retention that had occurred during the period of deployment would be lost within a decade. However, Parker and Irvine (2018) have argued that, with appropriate governance there are no obvious scenarios under which rapid termination might occur.

There is mixed evidence regarding how SAI deployment might affect polar regional climates. Some modelling scenarios suggest that SAI would have a protective effect on the Greenland ice sheet (Irvine et al., 2009). Others have suggested it may cause warming at the poles and in the tropics, whilst cooling the climate overall and that sea level rise may continue (although at a slower rate) (Applegate and Keller, 2015). Other research has found that attribution of climate side effects of Arctic SAI in real time was very uncertain, even speculative and requires more research (Jackson et al., 2015).

Choices about the spatial patterning of injections could also be made to balance different climate objectives, whether focused more on precipitation, Arctic Sea ice, or some regional responses (NASEM, 2021). Such choices remain subject to research and the outcomes are currently uncertain. It has been suggested that a SAI deployment that included a spatially patterned injection that increased forcing in the polar region might be most effective for limited SRM cooling scenarios (Macmartin et al., 2017). Modelling also suggests such profiles have the potential to increase the polar amplification (Collins, 2013). However, secondary effects may arise, including increasing heat travel from regions to the south into the Arctic which could counteract some effects of the SAI deployment (Tilmes et al., 2014). Modelling also suggests Arctic deployment of SAI could cause the inter-tropical conversion zone to move southward, negatively effecting climates in that region, including the monsoon (Nalam et al., 2017), unless it was balanced by comparable SAI deployment in the Southern Hemisphere (Nalam et al., 2018).

In addition, over Europe and Eurasia, the stratospheric heating caused by SAI may produce a stronger polar vortex, which lowers Arctic Sea level air pressure and increases the wind over the North Atlantic, leading to a shift in storm tracks that result in widespread warming with wetting over northern Europe and drying over southern Europe (NASEM, 2021, Simpson et al., 2019).

However, whilst modelling has shown deployment in the region would likely cool the Arctic in the first instance, changes it may cause in Arctic cloud cover and southern heat influx could counteract the direct effects of the SAI deployment (Tilmes et al., 2014). In addition, modelling suggests Arctic.

SAI deployment within the Arctic region on a seasonal basis, deploying aerosols during the spring and summer only may lead to reduced sea ice loss in those seasons, whilst year-round deployment may cause ice thickening as well as reduced seasonal sea ice loss (Kravitz et al., 2010). Also related to the Arctic (and peri-Arctic regions) a modelling study suggests a SAI deployment to reduce radiative forcing under the Representative Concentration Pathway (RCP) 4.5 scenario (IPCC, 2018) could lead to a reduction of permafrost carbon release, avoiding an approximated USD $8.4 trillion of economic losses by 2070 (Chen et al., 2020).

Current research activity

Currently research is predominantly modelling, and laboratory based (Berdahl et al., 2014, Irvine et al., 2009) or seeking a better understanding of governance issues (Horton et al., 2018; Macnaghten and Owen, 2011; Stavins and Stowe, 2019; Florin, 2020) and the social appraisal of the technology (Bellamy et al., 2012; Stilgoe, 2015).

The first SAI related physical sciences experiment ever to be conducted outside of the laboratory, The Stratospheric Controlled Perturbation Experiment (SCoPEx), was scheduled to take place in Arctic Sweden during 2021 (SCoPEx, 2019) to measure changes in the air perturbed by the balloon, in which between 100 grams (g) and 2 kilograms (kg) of calcium carbonate has been released, including changes in chemistry, aerosol density and how light is scattered (SCoPEx, 2019). The project led by the Keutsch Group at Harvard University sought to 'learn more about the efficiency of SAI and risks of solar geoengineering' but was called off in response to opposition from indigenous people and environmental groups (Reuters, 2021).

In a study of vulnerable populations, including in the North American Arctic, many respondents emphasized the importance of research being inclusive of people in developing countries, and they raised concerns that research might overlook local needs, worsen global inequalities (NASEM, 2021, Carr and Preston, 2018).

In 2019 a US Congress Bill approved research into the effects and risks of SAI (and MCB). Importantly this alluded to outdoor experimentation. In January 2020, the US National Oceanic and Atmospheric Administration (NOAA) was allocated USD $3.7 million for SRM modelling research. In July 2020, the financial year 2021 budget allocated a further year of funding at the same level, focussing on modelling work. In 2021, the US National Academy of Sciences called for a new USD $100–200 million solar engineering programme (NASEM, 2021) and SilverLining is co-ordinating a USD $3 million SRM research programme (SilverLining, 2020).

Socio-political considerations

There have only been a limited number of studies of public responses to SAI (Sugiyama et al., 2020 and Pidgeon et al., 2012).

Few non-specialists have participated in debates about the future of SAI. For example, indigenous peoples have figured widely in literature about climate-altering techniques as a key affected constituency, e.g., in the Arctic. However, some have noted that they have not yet been visible in debates about the future of SAI (Buck, 2018). More generally, there have been few attempts to explore justice concerns that vulnerable populations might harbour and how those concerns could inform ethics and policy discussions (Carr and Preston, 2017).

Governance

As with MCB, the need for governance of SAI arises from its capacity to intentionally effect the Earth's climate and social systems, structures and deeply held values about questions of justice, faith and rights (Shepherd, 2009).

It is unlikely that a SAI engineered climate could ever be constructed such that the resulting climate was perceived as optimal by all states, immediately creating a complex governance challenge (Ricke, 2013). For example, some countries might favour less ice in the Arctic, opening up access to resources and other benefits, whilst others may favour an increase in ice coverage. However, were it possible to reach global consensus about a 'new' temperature, through some as yet unidentified process or mechanisms, Ricke et al., (2013) suggest it may, then, be straightforward for states to agree how much SAI should be deployed and how to monitor it.

A deployment of SAI could potentially give rise to security governance issues, sowing mistrust or tensions.

C2G (2019b) provides a more detailed exploration of the governance, geopolitical and security issues associated with SAI and other SRM techniques in its Evidence Brief: Governing Solar Radiation Modification.

Table 3 – A summary of Arctic relevant SRM techniques

	TECHNIQUE	READINESS	ACTIVE RESEARCH AREA	GOVERNANCE FRAMEWORK	SOCIAL ACCEPTABILITY
 MARINE CLOUD BRIGHTENING (MCB)	Seeding and whitening clouds above ocean surfaces, likely using sea salt spray, to redirect some solar radiation back toward space. There is a potential for rapid regional cooling delivery directly on deployment. Estimated cost per year of per unit of radiative forcing Watt per square metre (W/m2) is $200 million[1]	Technology theoretical, based on natural analogues and computer models. Some for small scale outdoor experiments in 2020.	Both theoretical research and field work trials underway.	Within an exclusive economic zone (EEZ), governance would be for the host country. In international waters, customary international law applies. Regional variation in impacts (e.g., temperature and hydrological). Social acceptability remains uncertain.	Limited evidence that region specific target MCB may be socially acceptable. Indications that the expected controllability of MCB makes the technique more acceptable than SAI.
 STRATOSPHERIC AEROSOL INJECTION (SAI)	Reflective aerosols would be deployed in the lower stratosphere. Modelling suggests planetary cooling within a year is possible. Cost per year of per unit of radiative forcing are estimated to be between USD $17.5 and $100 billion (Smith and Wagner, 2018, Robock, 2020)[1]	Theoretical understandings of the technique are informed by studies of volcanic eruptions' climate effects. Mechanisms for delivery not yet developed. However, assessments suggest SAI would be feasible and less expensive than other techniques with similar potential.	Theoretical studies only to date. Field experiments are planned but pending governance deliberation. There is no co-ordinated research programme.	Which governance instruments may apply is unresolved. Relevant instruments are likely to include state and customary law, the CBD the UNFCCC and amended instruments such as air pollution instruments, the Vienna Convention and others. Evidence suggests deployment, or plans to deploy might strain international relations, institutions and cooperation. It may be that potential security issues could arise. Potential for moral hazard or mitigation deterrence. Constraints in climate science mean it may be challenging to attribute some effects of SAI, particularly at the regional scale, directly to a deployment – this may be resolved with research.	Evidence suggests significant social concerns about SAI. However, limited evidence suggests those concerns are less prevalent in the global south
 ENHANCING SURFACE ALBEDO	Making surfaces brighter, to redirect some solar radiation back toward space.	Small scale trials using silica spheres, bubbles and foams are underway. Potential technical limitations to scale, scope and longevity of materials in situ.	Limited	Regulatory and legal measures include customary international law, the London Protocol, CBD and UNCLOS s, but these may not be comprehensive and would apply to ocean-based activities only. Regional variation in impacts (e.g., temperature and hydrological) are expected and will require governance. Environmental protection and food safety regulations.	Uncertain

1 A doubling of CO_2 from pre-industrial would create a radiative forcing of 3.7 W/m^2 (Salter 2008). -1W/m^2 would be the equivalent of reducing the warming effect of a doubling of CO_2 concentrations by 27%.

Other SRM possibilities

In addition to those described above several other approaches to SRM have been discussed in the literature. Given these have not been developed in much detail, only a brief review of each follows.

Cirrus cloud thinning (CCT) would seek to reduce the net warming effect of cirrus clouds by modifying their structure. Cirrus clouds' capacity to absorb and emit longwave radiation back down to Earth outweighs the cooling effect they provide through the scattering of light (Lohmann and Blaz, 2017). CCT would seek to change this balance by reducing the longevity of the clouds and by changing their optical properties by 'seeding' the atmosphere. Currently, modelling research is at an early stage and researching this approach in the atmosphere is very challenging (Lohmann and Gasparini, 2017). However, Lohmann and Blaz suggest that, if effective CCT were possible, it would be most effective in the higher latitudes such as in the Arctic.

Described as the 'White Roof Method' (Zhang et al., 2015), structures could be built using light coloured materials and existing structures, such as buildings and roadways, resurfaced to increase their albedo. However, the net temperature effect of this measure is likely to be trivial, or one of warming, as locally affected surfaces would constrain moisture transport, and hence diminish cloud formation, meaning that more solar radiation would reach the Earth's surface (Jacobsen and Hoeve, 2012). This approach would not be suitable for the Arctic because of the small number of available artificial surfaces and the transport related emissions that would arise from the geographically distributed nature of urban environments.

It is estimated the direct cost of painting sufficient structures and surfaces white to reduce temperatures would be USD $300 billion per year, making the White Roof Method one of the least effective and most expensive of all possible climate-altering techniques (Shepherd, 2009).

It could be possible to enhance plant albedo through selective breeding and by genetically modifying plants (Ridgwell et al., 2009). The direct costs have not been estimated in any detail, and the effects of the required changes on disease resistance, growth rates, market price of food and drought tolerance are uncertain (Ridgwell et al., 2009). In the context of a world struggling to grow and distribute sufficient food (UNFAO, 2009), the challenges of diverting effort toward crops with increased albedo could be too great to make this a practicable option (Shepherd, 2009).

A range of Space based techniques have been proposed. However, they contain such great uncertainties regarding technique, direct and economic costs, risks and effectiveness as well as lengthy timescales that their implementation, even in the next hundred years, is probably unrealistic (Shepherd, 2009). For example, one option would require the deployment of ten trillion refracting disks of 60 centimetres (cm) in diameter, fabricated on Earth and launched into space to sit at the Lagrangian Point (where the gravitational attractions of the Sun and Earth balance), 1.5 million miles from the Earth's surface (Angel, 2006). Another would deploy a 5.5 Km2 reflector in near Earth orbit, to achieve a 2% reduction in solar radiation (Angel, 2006, USNAS, 1992).

SECTION II: GOVERNANCE

Introduction

The purpose of this section is to briefly review existing legal instruments and to highlight the most important governance issues and provisions but does not analyse them in depth. More information is available in the C2G Evidence Briefs on Carbon Dioxide Removal and its Governance and Governing Solar Radiation Modification and Hubert, (2020), Reynolds (2018), Scott (2013 and 2015) and Redgwell (2011) have produced in-depth descriptions of international law and governance relevant to climate-altering techniques, for those who wish to explore further.

C2G uses the IPCC's definition of governance in relation to climate-altering techniques (IPCC 2018). Governance is not, then, only about instruments and rules. It also includes processes in which citizens engage during the social appraisal of technologies as they evolve from ideas on to their various trajectories (Macnaghten and Owen, 2011, Stilgoe, 2015). Section 2 of the C2G Evidence Briefs on CDR and its Governance and Governing SRM provide more detailed information about a range of generic governance issues and about the international frameworks or instruments are relevant to climate-altering techniques mentioned below including:

- reporting monitoring and verification of CDR;
- 'moral hazard' or 'mitigation deterrence';
- risk-risk trade-offs;
- incentives;
- customary international law; Convention on Biodiversity (CBD) (CBD 2008);
- London Convention 1972 and the 1996 London Protocol (IMO 2016);
- UN Convention on the Law of the Sea (UNCLOS) (UN 2009);
- UN Framework Convention on Climate Change (UNFCCC) (UN 1992) ;
    - Paris Agreement 2015 (UNFCCC 2015);
    - Kyoto Protocol;
- International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL);
- Vienna Convention on the Protection of the Ozone Layer (UNEP, 1985) and the 1987 Montréal Protocol (UNEP, 1987);
- Environmental Modification Convention (ENMOD) (UN, 1977); and,
- Convention on Long-Range Trans Boundary Air Pollution (CLRTAB, 1979).

In addition, this section also discusses the potential role of the Arctic Circle, other fora and research governance.

Customary International Law

The general norms of customary international law as it relates to international environmental law would apply to climate-altering techniques in the Arctic including the duty to prevent transboundary harm, duties of international cooperation to undertake transboundary impact assessments and to consult and notify, and the precautionary principle.

The United Nations Convention on Biodiversity (CBD)

The 1992 CBD is one of the few conventions to have discussed approaches to climate-altering directly. Whilst the CBD position on the techniques appears strong and sends a governance signal it is not binding, and country participation is not universal (it excludes the US), and it only relates to the conservation of biodiversity and the sustainable use of biological resources. The limitations of the CBD highlight that, individual extant protocols and conventions as currently constructed, could only form an incomplete basis for global regulation (Hubert, 2020, Redgwell, 2011).

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the London Convention) 1972 and the 1996 London Protocol

The purpose of the Protocol is to protect and preserve the marine environment from all sources of pollution, and, in particular, from the dumping of wastes and other at sea. The Protocol directly addresses climate-altering techniques, and it is evolving in the context of the debate about 'marine geoengineering'.

Importantly, parties to the Protocol are developing the first legally binding framework for the governance of marine 'geoengineering' (Hubert, 2020). This seeks not only to protect the marine environment, but also seeks to be adaptable in response to technological and research progress.

United Nations Convention on the Law of the Sea (UNCLOS)

UNCLOS is an evolving Convention, and an intergovernmental process is in progress that is expected to lead to an international legally binding instrument under the Convention on the conservation and sustainable use of marine biodiversity of areas beyond national jurisdiction (Hubert, 2020).

In 2017, the General Assembly convened an Intergovernmental Conference to consider the recommendations of a Preparatory Committee for a proposed international legally binding instrument under UNCLOS regarding the conservation and sustainable use of biologically diverse marine environments in areas beyond national jurisdiction (UN, 2020). As this process evolves, it may develop importance for the future governance of marine CDR.

UN Framework Convention on Climate Change (UNFCCC)

Adopted in 1992 the UNFCCC provides an overarching framework to intergovernmental efforts to tackle climate change, its objective is the *'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'* (UN 1992) and it is likely that it will play a significant role in the global governance of CDR. However, what that role might be, and how it might relate to SRM is unclear at this time.

The Paris Agreement

The Agreement requires Parties to communicate a nationally determined contribution (NDC) every five years, setting out planned domestic mitigation efforts. Each successive NDC is required to demonstrate a progression and represent highest possible ambition.

Craik and Burns (2016) have identified four ways in which it is expected to influence the future direction of CDR, as detailed below.

- CDR may arise directly out of the Agreement's objectives, building on the inclusion of 'removals' that have been present in the UNFCCC since 1992. (GESAMP 2019).
- CDR techniques fall within the scope of Article 4, which includes CO_2 removals as a contribution to the mitigation commitments.
- The inclusion of CDR techniques in NDCs will raise legal questions about technological readiness and equity implications.

The Kyoto Protocol

The Protocol would not explicitly encompass several of the Arctic appropriate CDR techniques discussed above, including DACCS and oceanic fertilisation or enhanced weathering and the provisions were not designed for the scale of removals required for the Paris Agreement's long-term temperature goal.

The International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL)

Reviews of international governance mechanisms pertinent to climate-altering techniques have generally not discussed the Convention, although Talberg et al. (2017) does mention MARPOL in relation to ocean fertilisation.

The 1985 Vienna Convention on the Protection of the Ozone Layer (UNEP, 1985) and the 1987 Montréal Protocol (UNEP, 1987)

Given that the injection of aerosols and, in particular, sulphates may deplete stratospheric ozone, the Convention and Protocol may both be applicable to SAI. However, the scope of their applicability to SAI is currently unclear.

The 1977 Environmental Modification Convention (ENMOD) (UN, 1977)

ENMOD is not expected to be applicable to climate-altering techniques, aside, potentially, from SAI given they are generally considered not to be usable as a weapon (Rayner, 2017).

The Convention on Long-Range Trans Boundary Air Pollution (CLRTAP, 1979)

This Convention is aimed at protecting against specific pollutants, this creates a paradox in that the techniques described in this brief may not be polluting under the terms of the Convention, and, may or may not be considered to be a pollutant even if covered by the Convention in the context of their ameliorating effects on anthropogenic GHGs, in themselves considered as pollutants, although not listed in the Convention.

The Arctic Council

Established by the Ottawa Declaration in 1996, the Arctic Council is a high-level intergovernmental forum that aims to promote cooperation, coordination and interaction among Arctic States. It takes an interest in sustainable development and environmental protection. The Council is comprised of eight Arctic States – Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden and the US. Six Permanent Participants, which have full consultation rights within the Council's decision making and negotiations, represent organisations of Arctic Indigenous peoples. In addition, observer status is open to non-Arctic states, global and regional inter-governmental and inter-parliamentary organisations and other non-governmental organisations. Currently, 38 states have been approved as Observers to the Council.

Whilst the Council has no legal powers, it can operate through the exercise of influence and 'soft-law'. Providing a location where it is possible to explore contested agenda and construct consensus, consent or concord around governance issues. For example, the Council has agreed non-legally binding mechanisms that establish a shared vision for action in the form of an Agreement on Enhancing International Arctic Scientific Cooperation and an Arctic Council Framework for Action on Enhanced Black Carbon and Methane Emission Reductions.

Climate change has played an important role in the work of the Council, and they have produced important environmental evidence in the form of reports on snow, water, ice and permafrost in the Arctic (SWIPA, 2017 and 2019) and regional reports on adaptation in the changing Arctic (AACA, 2018).

In summary, the Arctic Council is an important location for international dialogue and cooperation on issues related to climate change in the Arctic and may have the potential to provide leadership in the currently fragmented emerging climate techniques governance landscape.

The Arctic Circle

The Arctic Circle is the largest network of international dialogue and cooperation on the future of the Arctic. Participants include governments, organisations, corporations, universities, think tanks, environmental associations, indigenous communities, concerned citizens, and others interested in the development of the Arctic and its consequences for the future of the globe (AC, 2021) making it potentially a useful location within which to explore climate-altering techniques and consider their potential research, development, deployment and governance.

Research governance

New evidence from research may help inform decisions about which, if any climate-altering techniques should be developed or deployed in the Arctic, when and by how much.

Whilst uncertainty is unlikely to ever be resolved (Stirling, 2008), further research may help reduce some of it, easing some of the governance challenges described (Mace, 2018). Addressing this research need is a governance challenge, for example, it is unclear how knowledge gaps will be identified, research agenda set, and funding will be secured and provided to appropriate researchers, particular in the context of research beyond national boundaries within global commons such as the Arctic.

Where the research/application governance boundary lies, is unresolved and it has been questioned whether there should be any delineation between the two, or whether the evolution of techniques through to testing at scale should be treated as a continuum for governance purposes (SRMGI, 2011 and Parker, 2014).

Reflecting these complex research governance challenges, several non-binding codes of conduct have been developed, such as the Oxford Principles (Rayner et al., 2013), the Asilomar Principles for Research into Climate Engineering Techniques (Asilomar, 2010), the Code of Conduct for Responsible Geoengineering Research (Hubert, 2017) and the Academic Working Group on Climate Engineering Governance (AWG, 2020).

Publics and their role in governance

Given that the techniques described in this brief are accompanied by questions about risks, benefits and uncertainties and are politically and economically complex, and because they may all cause some environmental damage with differential effects on communities, as well as positive gains, it is suggested (Buck, 2019) that citizens' perspectives on how these techniques move forward should be drawn into the processes of governance deliberation at the earliest stage in a mode of co-production.

Other fora or processes

In addition to those discussed above, other United Nations (UN) bodies that may be involved, in due course, in the governance of climate-altering techniques include: the UN General Assembly, the UN Security Council, the UN Development Programme (UNDP), the International Law Commission (ILC), the High-level Political Forum on Sustainable Development (HLPF), the UN Educational, Scientific and Cultural Organisation (UNESCO), the Food and Agricultural Organisation (FAO) and The World Meteorological Organization (WMO). For a review of how these bodies may engage in the future see Hubert (2020). Other IGOs that address economic, social, peace and security areas may also play a role in the evolving governance and, with their ability to make rules and exercise power within their member countries they have become essential actors in the international community of actors engaged in the governance of climate-altering techniques.

Other actors who may participate in governance processes in due course include nation states, regional bodies such as the European Union, research groups, CSOs independent non-governmental organisations and commercial interests and publics.

Conclusions

If the global warming is to be limited sufficiently to achieve the Paris Agreement goals, the IPCC scenarios (IPCC, 2018) clearly imply that CDR techniques will have to be adopted as part of the response, and SRM may also be necessary to avoid overshoot. The Arctic region plays a key role in the global climate and is undergoing rapid warming and change. It has been considered by some interested and affected parties to be an appropriate location in which to develop and deploy novel climate-altering techniques in response to these changes.

This briefing has explored the technical readiness, current research, applicable governance frameworks, and other socio-political considerations of the range of options that may be suitable for consideration in the Arctic region. Further, an overview of key instruments relevant for the governance of the techniques is offered. It is clear from this analysis that further research, especially in terms of potential removals capabilities and costs, and debate about the techniques, and how they might be best governed will be important before any final decisions about their deployment and long-term management can be taken.

Moving forward, we encourage open and informed conversation about the construction of effective and inclusive governance of these techniques, which should include consultation with a broad range of stakeholders with a view to helping deliver a safe, socially acceptable and environmentally appropriate future.

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