Humanity's Urgent Moral Imperative: Returning the Planet to a Proven Safe State

Abstract

The study is motivated by a desire for the planet to be returned to a guaranteed safe, sustainable, biodiverse and productive state. We acknowledge that this "planetary restoration" is only achievable if the mounting crises in the Arctic are quashed by rapid and determined intervention. We accept that these most serious of crises, involving abrupt climate change and multi-metre sea level rise, could amount to an existential threat for civilisation. The moral imperative is to intervene with utmost urgency, especially since the Arctic situation is deteriorating exponentially.

The global strategy to address gradual climate change has been to decarbonise the world economy by reducing emissions to net zero. But this strategy completely fails to address the imminent threats which arise from Arctic meltdown. This strategy must be changed quickly and drastically. The new strategy must include rapid intervention to stave off these mounting crises, using techniques such as identified in this study. Then, with continued intervention, the Arctic ice can be restored and, together with massive efforts on CO2 removal and methane suppression, the ultimate goal of planetary restoration is achievable within a few decades.

The three crises, yet to be fully acknowledged by the Intergovernmental Panel on Climate Change (IPCC), are:

- The accelerated melting of the Greenland ice sheet threatening a partial collapse which would cause tsunamis, a sudden rise in sea level and disastrous flooding.
- The accelerated disruption of the jet stream behaviour, due to rapid Arctic warming and sea ice retreat, threatening abrupt climate change which would have a disastrous impact on food security.

- The accelerated discharge of the potent greenhouse gas, methane, from subsea permafrost, threatening an outburst sufficient to make global warming unstoppable.

The results of the study are hugely encouraging. The judicious combination of the identified techniques could stave off the three crises and restore the Arctic ice. They should be considered for urgent research and development, in order that a ramp up to large-scale deployment can be started as soon as possible.

The global heating from greenhouse gases has warmed Atlantic and Pacific surface water flowing into the Arctic and triggered a vicious cycle of warming and melting: as the sea ice retreats it exposes open water which heats up and melts the ice from underneath, promoting further retreat in a vicious cycle known as “positive albedo feedback”. This started to happen decades ago, when global warming passed the 0.5°C mark. The ocean surfaces now need to be cooled to below this mark in order to allow sea ice to recover. The study identified SRM techniques which might do this, ideally in combination to maximise total effectiveness. But locally applied techniques, such as sea ice thickening, are required equally urgently: to help preserve sea ice and ice albedo; to avert catastrophe from Greenland collapse; and to slow the emissions of methane into the Arctic atmosphere.

Every effort must be made to support the development of techniques which significantly address the three crises. The techniques which are most critical for success must be fast-tracked. In parallel with this, quantitative scientific assessments, especially of cooling power requirements, must be made to ensure the sum total of interventions will be adequate – modelling can help towards this. And monitoring systems must be in place, ready for when deployment starts, in order to ensure safety and effectiveness.

Humanity's Urgent Moral Imperative: Returning the Planet to a Proven Safe State

1. Introduction

The Arctic's key role in cooling the planet through the high albedo of its snow and ice is well known. But the Arctic also has a key role in climate change and sea level rise. Urgent interventions are required to prevent an escalation of climate change and sea level rise to a catastrophic level. However restoring the Arctic ice provides a starting point for restoring the climate of the whole planet by 2050 and halting sea level rise as well.

The world's focus is currently on emissions reduction on a time-scale of several decades with the intention of slowing climate change and sea level rise. The crises in the Arctic are more immediately serious than the CO2 crisis and threaten to get out of hand without effective fire-fighting action over the next few years. The Arctic is warming much faster than the global average: perhaps 3-4 times as fast. The Arctic contains both a vast source of methane threatening to exacerbate that heating and the Greenland Ice Sheet whose meltdown or disintegration would raise sea levels catastrophically. And it has a crucial role in the control of global temperature and climate stability.

Two major changes in global strategy are required:

- *CO2 removal*: Hitherto the approach to climate change has been to tackle the emission of greenhouse gases, in particular CO2 by promoting the decarbonisation of the world economy. However the root cause of committed warming is past emissions which can only be addressed through CO2 removal (CDR). The heating power (aka climate forcing) from the accumulated excess of CO2 has reached 2.0 W/m2, averaged globally, or about 3.0 W/m2 if you include other greenhouse gases (GHGs) [1]. The achievement of net zero emissions only slows that heating; thus the mean global temperature will continue to rise after net zero is reached [2]. CO2 removal (CDR) on a trillion tonne scale is urgently required to reduce that forcing significantly but the achievement of a target such as 300 ppm will inevitably take a number of decades [3].

- *Refreezing the Arctic*: Meanwhile the Arctic is heating several times faster than the global average, without any effective action to halt and reverse that heating, let alone deal with the potentially catastrophic consequences. There are a number of feedback loops which are accelerating that heating [4], which means that halting and reversing the heating becomes significantly more challenging for every year of delay. Hence the deployment of cooling techniques with sufficient power is extremely urgent.

However, if these two changes in global strategy are adopted and lead to prompt interventions (such as investigated below), the crises in the Arctic can be averted and the world set on a path for climate restoration and a halt to sea level rise. The planet can be restored to the proven safe state in which our modern civilisation developed. This is our ambition.

2. Saving the sea ice is crucial for climate restoration and a safe future

It is becoming increasingly apparent that refreezing the Arctic is an essential component of any plan for climate restoration. Refreezing the Arctic involves reversing several dangerous trends, helping significantly in the restoration of favourable conditions elsewhere on the planet. But halting these trends has to be done quickly. Warm surface water from the Atlantic and Pacific has been entering the Arctic Ocean in ever larger quantities. And there is continued build-up of positive feedback – especially albedo and methane positive feedback. A new positive feedback to Arctic warming is emerging, with both the meandering of the polar jet stream and the wandering of the polar vortex bringing in warmer air from the south.

The rapidly warming Arctic risks the Arctic becoming locked into a relatively low albedo state, with sea ice almost absent some months of the year and with much less snow and ice on land [5]. This would have at least five serious global repercussions: on ocean circulation, on global weather patterns, on sea level rise, on methane emissions and on albedo loss:

- The Atlantic Meridional Overturning Circulation (AMOC) has already been weakened. The effect on AMOC of the incursion of warm Atlantic and Pacific water is as yet unknown; but disruption of AMOC is thought to have caused major climate change in the past – for example glaciating much of Europe during the Younger Dryas [6].
- Arctic warming is already affecting weather patterns at mid latitudes; but the effect of this new state could be to lock in a new regime of atmospheric circulation over much of the planet, producing abrupt climate change [7].
- The Greenland Ice Sheet has already become the main source of sea level rise globally [8]; but further Arctic warming would continue the escalation, risking disintegration of the structure of the ice sheet itself with giant blocks of ice cascading into the sea and creating tsunamis and abrupt sea level rise [9].
- The escalation of methane emissions from the ocean seabed is already cause for concern [10]; and if emissions reached the gigaton per annum level, methane could drive global warming beyond any possible control [11].
- As for albedo loss, the retreat of snow and sea ice has already contributed to the planet's excess heat budget by as much as 1.0 W/m2, i.e. half of CO2's contribution [12]. It is inexplicable that this major climate forcing agent is missing from IPCC documents. If the Arctic Ocean becomes almost free of ice for several months of the year, and snow cover on land masses continues to decline, their contribution to albedo loss could reach 2.0 W/m2 or more [13].

3. The Arctic and global heat budget

While CO2 contributes 2.0 W/m2 to planetary heating, other greenhouse gases contribute an addition 1.0 W/m2 heating; of this about half is due to methane [14]. Methane has a global heating effect 86 times greater than CO2, weight for weight, summed over 20 years. This means that one tonne of methane added to the atmosphere is equivalent to adding 86 tonnes of CO2, if you total each of their heating effects over 20 years [15]. Methane contributes about 0.5 W/m2, with other non-CO2 GHGs contributing the other 0.5 W/m2. A growing contribution to the positive forcing side of the planet's overall heat budget is from albedo loss: the Arctic albedo loss since 1979 (when satellite measurements began) is estimated to be between 0.7 and 1.0 W/m2. This would make the total positive forcing around 4.0 W/m2.

One result of this huge surplus of positive forcing, which has doubled over the past 40-50 years, is that temperatures are now rising at an underlying rate of about 0.25°C per decade globally [16]. However in the Arctic they are rising several times faster, now at up to 1.0°C per decade. This "Arctic Amplification" (AA) is largely due to positive albedo feedback: as the sea ice retreats it exposes open water which absorbs sunlight, which in turn encourages more melting of the sea ice from below and further retreat [17].

The albedo feedback is exacerbated by the increasing incursion of warm saline water from the Atlantic and Pacific into the Arctic. The refreezing of the sea ice in the autumn/fall is tending to occur later each year, for example with a record low for October 2020 in the Barents Sea [18].

Modelling by Stranne et al suggests that, in the early Holocene, the Arctic switched from a high-albedo state with perennial ice to a lower-albedo state with seasonal ice as a result of peak radiative forcing from the Milankovitch cycles [19]. After a few thousand years there was a switch back. The switch over and back involved a hysteresis loop (shown in the Stranne paper): ice thickness suddenly falls from an average of 2 metres thickness down to 1 metre as radiative forcing/heating increases by 0.5 W/m2 over a threshold; and conversely the ice suddenly thickens when the forcing is reduced by the same amount. We could be witnessing, or about to witness, such a switch transition from perennial sea ice to seasonal sea ice in the Arctic today. According to some sources, the mean ice thickness at the end of summer 2020 was about 1 metre, though PIOMAS gave it as about 2 metres [20].

4. Radiative cooling of the Arctic using SRM and ERM

In order to assess interventions to cool the Arctic it is necessary to establish an approximate figure for the maximum cooling power requirement.

The Arctic Ocean is being heated by the incursion of Atlantic and Pacific water, heated as a result of anthropogenic global warming. A vicious cycle of warming and melting has been triggered by this injection of heat. There are a number of positive feedbacks in operation, of which the sea ice retreat and snowline retreat are probably the greatest. If the Arctic is to be refrozen to restore snow and ice levels, then the feedback loops need to be broken. The positive albedo feedback can be calculated using satellite observations of snow and sea ice retreat. The heating power through albedo loss in 2019 is estimated to be in the range 0.6 to 1.0 W/m2; this would require 0.3 to 0.5 petawatt of cooling power to counteract it directly. Most of this heat is being accumulated in the Arctic Ocean, causing the temperature to rise [21].

In addition, Atlantic and Pacific water continues to heat the Arctic. It is problematic to establish how much heat this provides, but it could amount to as much as 1.0 W/m2 again, judging by the change in Milankovitch signal which was able to switch the Arctic into a low-albedo [22]. Thus to counter this heating as well as albedo loss could require as much as 1.0 petawatt of cooling power.

There are a number of much smaller positive feedbacks, but also some negative feedbacks such as the cooling by thermal radiation and evaporation from water exposed by sea ice retreat or by the now widespread breaking up of sea ice at the end of summer. The 1.0 petawatt of cooling power is thus considered a reasonable maximum requirement for engineering assessment.

No method of direct cooling of the Arctic Ocean has been identified which could provide the required cooling power. Cloud manipulation methods are limited because of its area of 14m km2, a small fraction of the planet's 510m km2. However there are two global cooling approaches, MCB and SAI, which could together provide the required cooling power and inject it into the Arctic Ocean [23]. Their application would cool the surface water flowing into the Arctic Ocean from the Atlantic, the Pacific and the many rivers of Siberia, Canada and Alaska. Local radiative cooling methods can help in conjunction with physical interventions such as sea ice thickening. Three such methods are mentioned below.

4.1 Global SRM to cool the Arctic

Marine Cloud Brightening (MCB)
Cloud physicist John Latham suggested that the amount of solar radiation reflected by clouds could be increased by adding additional salt particles from sea water [24]. Clouds reflect sunlight back to space, thus providing cooling. If the number of water droplets inside the cloud increases and their size decreases, the reflectivity of the cloud increases, making the clouds brighter and longer lasting, reflecting sunlight and increasing cooling. At least two teams are undertaking lab experiments, modelling and designing dispersal equipment for future, initial, small scale field trials to prove the concept.

An alternative approach for MCB is to stimulate phytoplankton blooms. These create DMS which produces significant cooling, even in the Arctic, through its cloud brightening effect [25].

MCB could have a theoretical limit of about 1.5 petawatt cooling power [26]. Therefore it would be safest to employ it in conjunction with SAI, which has no theoretical limit. However SAI is a relatively blunt instrument; MCB has advantages of precision in timing, location and control.

Stratospheric Aerosol Injection (SAI)
Stratospheric aerosol injection can provide a powerful cooling effect. It is claimed that SAI alone could restore Arctic ice [27]. The aerosol particles reflect sunlight back into space, but also reflect some thermal radiation from the planet's surface back to the surface. The former effect normally dominates. The injection of SO_2 into the stratosphere during the eruption of Pinatubo in 1991-2 produced about 0.5C global cooling, but had a heating effect on the Arctic during winter. Thus use of SAI to cool the Arctic critically depends on injection during the spring and summer in such locations and at such a height that most of the aerosol falls out of the stratosphere before the winter. The slow Dobson-Brewer meridional circulation of stratospheric air from equator towards the pole should cause the aerosol to fall out in a few months [28]; however winds in the stratosphere could distribute the aerosol widely, lessening the cooling effect on the Arctic. Another factor is the potential effect of SAI on ozone depletion. Careful choice of location,

height and timing of injection is necessary to produce optimum cooling without significant ozone depletion.

Alternatives to SO2 are being considered for SAI which avoid the ozone problem, but they may be more expensive to deploy at the required scale and may not be ready soon enough to halt the dangerous trends of heating and melting in the Arctic.

There is also the MEER project which is developing means to brighten surfaces by using reflective materials [29]. Envisaged applications include increasing the albedo of cities around the globe. The author has not yet evaluated this technique to compare it with MCB or SAI.

4.2 Local cooling methods

Cloud thinning and cloud removal
This is a promising technique of Earth Radiation Management (ERM) which could be used locally to help restore ice and snow by allowing increased thermal radiation into space, thus cooling the surface whether it is snow, ice, land or water. Research has established the feasibility of Cirrus Cloud Removal (CCR) [30]. The amount of radiative cooling power which could be produced over the Arctic as a whole is much less than the required 1 petawatt as per estimate above. However CCR could be used globally in the

Surface brightening with micro-spheres
Ice911 uses non-toxic silica micro-spheres placed in limited strategic locations which act to reflect sunlight, thus assisting first year ice to act like more reflective multi year ice and lasting longer through the Arctic summer [31]. The micro-spheres are hollow, a few micrometres in size and not harmful if ingested. The team have undertaken extensive trials on lake ice and are seeking permission and funding for initial trials on sea ice. Modelling suggests that substantial ice restoration is achievable throughout the Arctic by treating some limited areas of sea ice at specific times of the year. Long-term tests are required to determine the durability of the bead's reflecting effect. Other suggested means of brightening, such as larger spheres, have suffered from algal contamination. Although the cost of material may be low, the cost-

effectiveness of periodically distributing the micro-spheres over large areas of sea ice could be problematic.

Surface brightening with persistent nano-bubbles

Nano-bubbles could be used to brighten the surface of exposed water in the Arctic, cooling the water below. There has been some detailed research on this technique [32]. The surface micro-layer of the ocean is rich in organic surfactants. Nano-bubbles introduced into this layer by seawater-encapsulated air can last for months because of the protective shells of surfactants, ions and gas-saturated seawater that form around them. Nano-bubbles are a natural part of the environment; they reflect solar energy particularly effectively whilst being benign to marine life. They are in, rather than on, the water surface micro-layer, thereby allowing evaporation. They reflect sunlight, thus shading the deeper water below. Warming of the micro-layer increases evaporation which contributes to the cooling of the deeper water below. The additional water vapour in the atmosphere releases its heat energy typically overnight into space as it condenses as dew, fog, marine cloud or rain. These cooling effects can be maximised by injecting nano-bubbles of the optimal size into the micro-layer, using low-cost, solar-powered units called "fiztops" because they are designed to generate a fizz of bubbles from the underside of lightweight, conical or top-shaped units either anchored or free-floating in the ocean currents and gyres. Eventually, the air in the nano-bubbles dissolves in the seawater or escapes into the atmosphere.

Surface brightening with snow

The most natural means of surface albedo enhancement is by brightening with snow.

Where snow has retreated, more snow could be deposited, when the ground temperature is below freezing, by cloud seeding. This method is being used in the Himalayas to create snow on the mountains and increase river flow in spring [33]. Much careful monitoring of cloud and ground conditions would be necessary to make this technique work in the Arctic; but it is an extremely promising technique.

There has been a deposit of black carbon over much of the Arctic which has reduced the albedo. Also, when sea ice turns to slush, the albedo is greatly reduced. Thus depositing snow on areas of reduced albedo when the surface temperature is below freezing has potential.

Snow retreat could be slowed by making the snow more permanent. A chemical means has been suggested but not followed through, which is assumed to be because of intrinsic high cost.

Glacier snow and ice can be protected by plastic covering, but this approach is too costly on a large scale, e.g. over the Arctic sea ice or the Greenland Ice Sheet. Also there would be severe environment problems for such large-scale use of plastic.

Increasing outgoing thermal radiation by ERM
Cloud thinning and removal by cloud seeding has potential to increase outgoing thermal radiation [34]. This method falls into a class of Earth Radiation Management (ERM) techniques. The best known is Cirrus Cloud Thinning, where cloud nuclei of a certain critical size are introduced into the cloud with the effect of thinning or even removing it. This is the opposite of cloud seeding where the cloud is made to precipitate snow.

Such methods might be used locally when the conditions of cloud are appropriate. Thermal radiation into space can be as much as 100 W/m2 if there is no absorption by water vapour or clouds. The latent heat generated by sea ice thickening techniques (see below) could potentially be dissipated by direct radiation into space.

5. Arctic sea ice

It would be foolhardy to rely entirely on radiative cooling techniques, such as listed above, to prevent the Arctic becoming seasonally free of sea ice [35]. Some kind of ice management has got to be a major part of the solution. It would be designed to prevent the sea ice disappearing at the end of summer, and it would increase the albedo of the Arctic generally, thus having an overall cooling effect.

The importance of saving the sea ice is because of its reflective capacity or albedo. The sea ice has been retreating noticeably since the 70s. An acceleration of this retreat was noticeably by the mid-80s, indicating that positive, reinforcing feedback was dominating over negative, stabilising feedback. The main positive feedback is from the absorption of sunlight by exposed water as sea ice retreats. The sunshine warms the water down to considerable depth, and some of this heat contributes to the melting of the sea ice from underneath the following year, thus promoting further retreat. The main negative feedback is from the cooling of the exposed water by evaporation and radiation. This negative feedback reduces when the surface of the water freezes to form new sea ice in the autumn. The ice thickens by freezing from the bottom, as air temperatures above the ice fall below zero. The ice is an insulator, so the thickening gets slower as the thickness builds up.

Methods to preserve the sea ice and its albedo fall into two types: those which thicken the sea ice to make the sea ice last as long as possible through the summer; and those which remove ice in the autumn to maximise the cooling of the ocean water through evaporation and radiation.

5.1 Sea ice thickening

Sea ice thickening has the effect of releasing latent heat as the water freezes onto the surface of the ice. Some of this heat will be dissipated in the atmosphere and some directly radiated into space. The thickening would be done in the winter and early spring when the air temperature is well below freezing. It would be best done at times of low cloud cover, to maximise radiation into space, but these are also times when the air temperature tends to be lowest.

Note that, when the air is particularly cold, sea ice can be created where there was none by spraying droplets of seawater through the air onto the ocean surface. Once formed the sea ice can then be thickened. This technique is used by energy companies to construct ice platforms whose bases can get firmly anchored on the seabed, allowing drilling to proceed for months without disturbance from sea ice movement.

A further effect of sea ice thickening is to increase downwelling water as the created volume of sea ice melts, potentially strengthening the

Atlantic Meridional Overturning Circulation (AMOC) [36]. See also the section on methane below.

The choice of ice thickening technique will depend on the time of year and the state of the sea ice where the thickening is to take place. In the autumn, when there is little or no sea ice, equipment can be floated into position, anchored and subsequently cemented into position by naturally forming sea ice. (This is done for profiling buoys called "ice tethered profilers" which measure temperature and salinity in the water column.)

Ice Management research

The idea of pumping water onto ice to thicken it has been researched by a number of people, and this seems to be a promising technique for prolonging the life of sea ice, and hence its albedo cooling effect. One published research paper, recognising that "this loss of sea ice represents one of the most severe positive feedbacks in the climate system" is in the AGU journal [37]:

> "Here we investigate a means for enhancing Arctic sea ice production by using wind power during the Arctic winter to pump water to the surface, where it will freeze more rapidly. We show that where appropriate devices are employed, it is possible to increase ice thickness above natural levels, by about 1 m over the course of the winter. We examine the effects this has in the Arctic climate, concluding that deployment over 10% of the Arctic, especially where ice survival is marginal, could more than reverse current trends of ice loss in the Arctic, using existing industrial capacity. We propose that winter ice thickening by wind-powered pumps be considered and assessed as part of a multi-pronged strategy for restoring sea ice and arresting the strongest feedbacks in the climate system."

Ice shields

An ice shield concept has been promoted by the Climate Restoration Foundation [38]. This involves having a large number of wind-powered pumps distributed over the region where ice thickening is required. Each pump raises water from beneath the ice and distributes it over the area around the pump. This water freezes, and gradually builds up an ice shield in a convex structure. These structures can be put together to form a honeycomb matrix. Most of the ice shield is under the water line, and the shield could be built up until it grounded on the seabed, if required.

As the water freezes the air is warmed. The rising air will tend to form a vortex around the pump, carrying heat high into the atmosphere where it will dissipate. Thus one result of sea ice thickening is that heat from the ocean is taken into the atmosphere. This specific process of heat transfer could potentially be exploited to cool the ocean, even using a heat pump to generate power as an alternative to wind power. One of the ERM techniques (see below) might be needed to ensure that most of the heat taken from the ocean escapes into space rather than warming the atmosphere. This remains a problem with the heat transfer idea if done on a large scale.

The ice shield concept has raised a number of issues concerned with the engineering design. In this concept it is assumed that the ice builds up around the wind pump in a shallow conical structure; but at very low temperatures the water could freeze immediately. The flow of water from the central point has therefore to be controlled so it doesn't freeze too quickly and a large circular area can be covered evenly.

Pumping from the edge
An alternative design has a number of pumps around the edges of a hexagonal ring of ice blocks, squirting or spraying water over the central area under autonomous control to produce the desired distribution of ice thickness to create a flat or concave surface within the ring (compared to the convex structure of the ice shield above). For a hexagonal shield set in a honeycomb structure of shields, each vertex of the shield would share a pump with its two neighbours. The wind generators need not be collocated with the pumps doing the spraying. The spray guns would time their operation according to the direction of the wind to optimise efficiency of coverage. Tidal pumping may also be possible.

Like the ice shields, the hexagons can be connected with one another to form a honeycomb structure. Concave hexagons, with greater thickness around the edges, would give greater strength to such as structure.

Heat pump operation
An alternative to wind energy, or obtaining electricity through power lines, would be to use a heat pump. The heat pump generates energy by utilising the temperature difference between source and sink [39]. The source would be the water under the ice and the sink would be the air above the ice. In the process the air would be warmed and the water cooled. This energy would be used to lift the cooled water above the ice and thicken the ice with it. The latent heat released on freezing the water would further heat the air above the ice. However an updraft would be created to draw in more cold air.

There is uncertainty over the efficacy of such ice thickening on a large scale, because of its potential to warm the Arctic atmosphere. Thus, when considering ice thickening across a large area of the Arctic Ocean, the engineering design must consider disposal of the heat, either through direct thermal radiation from the freezing surface into space or through transfer of heat by convection to a high level in the troposphere where it can be radiated into space. This is why a combination of ice thickening with cloud removal (see ERM above) has considerable merit.

Sea ice arches and barriers
Sea ice thickening strengthen the ice and preserves it for longer during the melt season. Judiciously located ice thickening can slow the movement of ice towards places where it will melt more rapidly. The technique can be used to create a curved barrier of thickened ice in a great arc like a floating dam. Such arcs are known as "arches" where they occur naturally [40]. An arc of thick ice can block the passage of ice and icebergs through the narrow straits between islands, e.g. those of the Canadian Archipelago. This prevents their passage out into open water where they can be a hazard to shipping, e.g. in the North West Passage. Potentially large areas of sea ice can be maintained behind the barrier throughout the year, not only helping to cool the Arctic but also providing a safe habitat for seals, polar bears, etc. This is desirable for indigenous people who have relied on perennial ice for hunting. The thickening is done by pumping sea water onto the surface of the ice, using wind turbines for power. A location in the Canadian Archipelago would be suitable for trialling the technique.

A method to obtain a uniform thickness of ice employs specially designed battery-operated vehicles (preferably autonomous) to spread the water [41]. There is already experience of ice thickening to strengthen tracks across frozen lakes to allow heavy transport across them, potentially throughout the year. A pattern of tracks across the Arctic sea ice could be produced, using the vehicles to transport of water along the tracks. A vehicle would squirt the water over the track behind it to solidify in a thin layer, building up the thickness of the ice a little at a time. The vehicle would stop periodically for a water refill and for battery recharge (or replacement of the battery with a freshly charged one to save time). The water would be pumped into the vehicle from pipes sticking down into water below the ice. The sea ice would need to be drilled at suitable intervals, say a kilometre apart, and pipes installed so that vehicles could obtain water to thicken the stretch of track between the pipes.

The creation of a barrier by such a method could have commercial benefit for the protection of shipping lanes on one side, besides having the benefits of helping to save the sea ice (and its cooling albedo, etc.) on the other side.

5.2 Sea ice removal

In naturally occurring polynias in the Arctic, the open water is swept free of ice by prevailing offshore winds. The ice gets piled up against existing pack ice. The water is cooled by evaporation and radiation. New ice is formed and the extruded brine sinks. The new ice is blown away, continuing the cycle.

Removal by icebreakers
A similar cycle is proposed for sea ice removal, where icebreakers are used to sweep the ice away instead of the wind. The ice is piled up, e.g. against the existing ice pack. The exposed water cools by evaporation and radiation. After new ice has formed, the cycle is repeated.

At the mid September equinox the sea ice reaches a minimum, with much of the remaining ice broken and still melting and with some new ice forming. The remaining ice, together with new ice, could be swept into piles leaving clear open water for maximum cooling. Strips of open water could be created, with the ice piled up into pack ice on either side.

When the air temperature is particularly low, the icebreakers could spray seawater onto the piled up ice fragments to cement them together and add further thickness, as for other methods of ice thickening.

An ice removal technique might be considered for the Northern Sea Route, north of Russia, where icebreakers may anyway be plying to and fro to keep sea lanes open.

6. Greenland Ice Sheet (GIS)

The Greenland Ice Sheet is in a critical condition, as its surface melts apace and its glaciers accelerate their discharge of ice. The GIS is losing ice mass at an increasing rate due an imbalance of ice accretion and ice removal. This ice mass loss translates into sea level rise (SLR), and now GIS is contributing more to SLR than the expansion of the oceans from global warming [42]. Some of the surface meltwater percolates through the ice sheet to form subglacial lakes; these eventually drain to the base of the ice sheet leaving cavities in the ice. The rest of the meltwater collects in melt-ponds (which can be sizeable lakes) and then flows out through great holes in the ice called "moulins" and reaches the base of the ice sheet more rapidly. The meltwater between a glacier and the rock or gravel surface beneath it causes hydraulic lifting which lubricates its descent. As the volume of meltwater has increased, the glaciers' descent has been accelerating. This acceleration is also promoted by increased melting from warm ocean water licking at glacier terminations and causing more rapid calving of icebergs. This acceleration, coupled with decreased integrity of the ice through being riddled with cavities, is extremely dangerous, since a shock, such as an earthquake of collapse of glacier side-wall, could cause an avalanche of kilometre sized chucks of ice into the sea. No doubt such avalanches have occurred in the past, e.g. with the collapse of the Hudson Bay Ice Dome in the Early Holocene [43]. A partial collapse of the GIS in this way could lead to mega-tsunamis and a sudden rise in sea level of a metre or more. Thus it is of utmost urgency to find means to slow the acceleration of glacier descent, both by reducing melt at the ice sheet surface and by reducing melt at glacier termination.

6.1 Reducing surface melt and meltwater penetration

Surface brightening

The ice sheet surface can be brightened to reduce melt in the spring and summer. The seeding of clouds could deposit fresh snow; and the removal of the clouds would allow increased ERM cooling (see above). However, by the time the melting is underway the surface temperature may be too high for snow to accumulate. So this method appears problematic. Brightening the surface with micro-beads (see above) appears similarly problematic because the beads are unlikely to adhere to the surface when melting is underway.

Ice thickening to slow surface melt and run-off

The ice on melt-ponds can be thickened as soon as the air temperature falls sufficiently below zero. However in spring the meltwater might simply collect on the surface of the ice; and the presence of meltwater leads to higher air temperature on into the summer. So this method has not been considered as a serious candidate for meltwater reduction.

Removal of meltwater from melt-ponds

A simple way to remove meltwater would be spray it away from the ponds to fall as snow, once the air temperature had fallen sufficiently after the summer melt season. The power would be supplied from wind generators suitably situated above the ponds. Building up the snow around the ponds would help to maintain snow cover and its associated albedo for the following melt season.

An alternative idea, perhaps applicable near the coast, would be to pump from melt-ponds out through channels or pipes which lead directly to the sea. The energy for pumping could come from wind turbines situated in windy locations above the melt-ponds. The drop towards the sea end could enable the generation of hydro-electric power. Electric power could be supplied back to the pumps through a grid laid down across the ice sheet, thus obviating the need for wind generation, once the grid was in place. (The surplus power could perhaps be sold as a source of income for the project if a means of “transporting” this power can be found, e.g. by electric transmission through high-voltage direct-current cable or by conversion to hydrogen fuel.)

Whichever techniques are adopted, there is little doubt that the draining of melt-ponds would reduce the risk of glacier collapse. Sudden draining of a melt-water lake can cause a surge of water at the base of a glacier, causing its sudden acceleration. This has been observed [44].

6.2 Slowing the glacier calving

Ice barrier to slow glacier calving
Ice thickening can be used to slow down Arctic and Antarctic glacier movement to limit sea level rise and the potential impacts on coastal cities and ecosystems. One method is to create an arc of thickened ice across a fjord or between islands to prevent the passage of icebergs, see above. A particular technique has been proposed where a vertical wind turbine mounted on a buoy would provide the power for the pump to pump sea water onto the 'melange' (a mixture of icebergs and sea ice) at the toe of calving glaciers [45]. This would act as a buttress to calving glaciers – thickening the melange and prolonging summer melt. It is known that ice shelves form a natural buttress to slow glacier descent; hence a technique such as above which creates a buttress must have merit.

Hydrological method to slow glacier calving
The calving of icebergs has been accelerated by the increasingly warm saline Atlantic water melting at glacier terminations. This water enters a cavity under the ice termination and then doubles back to return at a higher level to melt the ice. Though now colder, the resulting fresher ice is less dense than the more saline water entering the cavity and floats on top of it. Salinity beats temperature when it comes to density. Warm saline water is heavier than cold fresher water.

Any means to disrupt this process should help slow the calving. There has been a proposal for building giant sills under the termination of Antarctic glaciers to ground them, but cost and logistics could well be prohibitive [46].

7. The methane threat

A catastrophic outburst of methane could significantly exacerbate global warming. An extended period of emissions at the gigatonne level would be sufficient. Subsea permafrost in the Arctic contains upwards of a thousand gigatonnes of organic carbon, much in the form of a methane hydrate ice called clathrate. The clathrate is formed under conditions of high pressure and low temperature. Permafrost is already beginning to thaw and release methane gas, which is bubbling up in great plumes off the coast of Siberia [47]. But sudden, explosive release is possible if the pressure on clathrate is suddenly released. (This is thought to be the cause of huge craters in Siberia. And there are signs of such releases on the seabed in various places around the world.)

Thus continued heating of the Arctic seabed threatens a destabilisation of the clathrate deposits and sudden release of gigatonnes of methane. This may have happened in the Storegga collapse, about 8,000 years ago, causing a tsunami on the NE coast of Scotland.

There is also the possibility of the sudden release of free methane from underneath the permafrost as it thins, being heated from below by geothermal energy and from above by the warming ocean. Perforations of the subsea permafrost result in taliks which have been discovered in large numbers on the East Siberian Arctic Shelf (ESAS) [48].

7.1 Methane suppression

Techniques for cooling the Arctic seabed, particularly in the area of continental shelf off Alaska and Siberia, would help to slow the permafrost thaw. A thin layer of cold briny water on the seabed might be sufficient, since it would be considerably denser than the water above.

One proposed technique is to create brine from seawater when it freezes. (This occurs naturally in Antarctica when sea ice forms, streams of brine suddenly sinking to the seabed where living creatures are frozen alive.) If seawater is sprayed onto the sea ice in sub-zero temperatures, the freezing of the water extrudes brine which percolates to the base of the newly formed ice forming a slushy layer. When the sea ice is melted from below in the summer, the brine is released and sinks to the seabed.

This has been suggested as a means to enhance the Atlantic Meridional Overturning Circulation (AMOC) but it also serves to cool the seabed [49].

Another technique would be to use a heat pump to cool the seabed. Ammonia could be the working fluid, evaporating in the water above the seabed and condensing in the atmosphere. Latent heat is absorbed from the water on evaporation of the ammonia, and released into the atmosphere when the ammonia condenses. The heat pump could generate power for local application or storage. This idea has not been evaluated.

7.2 Methane digestion in the water column

Where methane is emitted from the seabed in large quantities, the seawater becomes saturated with dissolved methane and the excess methane creates bubbles ascending through the water column. Methanotrophs occur naturally in the water column, digesting methane as it rises [50]. They require food and oxygen to flourish. This can be supplied by phytoplankton, e.g. diatoms. A technique for reducing the amount of methane bubbling to the surface and entering the atmosphere involves the creation of blooms of phytoplankton, typically using a cocktail of micro-nutrients to stimulate the blooms. An alternative technique involves the deployment of mats impregnated with phytoplankton.

Such techniques can also be used in methane-producing lakes, helping not only to suppress methane but to purify the water and promote a food chain, e.g. for the production of fish or prawns. This would have application over large areas of Siberia, Canada and Alaska, where water from thawing permafrost tends to collect in “thermokast lakes”. This thawing permafrost also produces vast quantities of methane, since the decomposition is anaerobic. In winter this collects under the ice. (At lower latitudes the purification of water can promote the production of rice in paddy fields while suppressing a major source of methane in the atmosphere.)

7.3 Methane destruction in the atmosphere

If methane is emitted into the atmosphere to increase the concentration significantly, it would be possible to destroy it by a catalytic chemical reaction. This is the basis for the Iron Salt Aerosol (ISA) method, enhancing the natural process of creating chlorine radical atoms that react with methane [51]. The reaction is catalytic such that each iron chloride molecule can destroy a number of methane molecules. The reaction is catalysed by UV light so the method is not applicable in the Arctic winter. However, if there was a megaton outburst of methane from the Arctic, significantly raising the atmospheric burden of methane, this excess might be reduced by ISA at scale. Thus preparation for large-scale ISA could be justified as a precautionary measure, while other methods of methane destruction are sought.

8. Conclusions

The ultimate goal of our endeavours is planetary restoration: returning the Earth System to a healthy state for human posterity – a state which is guaranteed safe, sustainable, biodiverse and productive. Such a healthy state can only be guaranteed if it is close to pre-industrial norms. But planetary restoration will be impossible without reversing the most dangerous trends, which are apparent in the Arctic.

The problem we set ourselves was to find plausible methods for addressing the major crises emerging as a result of an accelerated Arctic meltdown. These crises could potentially manifest as abrupt and catastrophic climate change, sea level rise and multi-megaton methane release. The necessary action to quash these crises turns out to be nothing less than a refreezing of the Arctic: offsetting the heating that has resulted from lost albedo; cooling the Atlantic and Pacific water which continues to inject heat into the Arctic; restoring the sea ice whose retreat has boosted methane emissions; halting the ice mass loss from the Greenland Ice Sheet. We recommend a judicious combination of albedo enhancement, radiative cooling and physical constraint. But albedo enhancement using stratospheric and/or tropospheric aerosols turns out to be absolutely essential to provide the necessary basic cooling power if we have done our engineering assessment correctly. These techniques are commonly referred to as Solar Radiation Management (SRM).

With so much at stake, every effort has to be made to ensure a successful stabilisation of the Arctic situation. This is a huge operation which will require, for a decent chance of success: multinational collaboration; brilliant management; detailed planning; independent evaluations; multiple skills and expertise; and careful use of the resources available, since they could be a limiting factor for some techniques.

Parallel development of alternative technologies should be encouraged and parallel deployment allowed where there is no interference. For example, different MCB techniques could be applied in different areas of the ocean at the same time as SAI is deployed in the stratosphere.

However our assessment of the engineering techniques shows a wealth of expertise and ingenuity for tackling the problems. It suggests that there is a good chance of overall success if given proper backing for development and deployment, with appropriate systems for safety, monitoring and continuous evaluation.

But public opinion is heavily against SRM. Here are the predominant arguments against SRM:

- SRM is intrinsically dangerous. However, the proposed SRM methods are all based on naturally occurring processes which cool the planet's surface without adverse side-effects. Additionally, much research has gone into identifying possible risks; and top modellers say that these risks can be circumvented or mitigated by appropriate careful application and monitoring.
- SRM is dangerous because, when stopped, the temperature will rebound – this is known as the termination problem. However, we urge that the levels of greenhouse gases in the atmosphere are reduced in parallel with the application of SRM, so that no such rebound is possible. SRM can be regarded as a stop-gap in this sense.
- SRM is morally wrong, because it allows polluters to continue polluting – it is a "get out of gaol free" card. This is the so-called "moral hazard" argument. However, reducing emissions is not

going to save the Arctic, and saving the Arctic is not going to affect emissions; so that does not seem to be a valid argument.

- It would be morally wrong to rely on SRM when it is politically unacceptable, and so the world should prepare for what will happen without SRM – e.g. a metre of more of sea level rise this century. However the starting point should be what is possible from engineering considerations and what has to be avoided. If SRM is necessary to avoid passing points of no return leading to inevitable catastrophe, then this fact has to be faced by the international community. One such catastrophe would be the sudden destabilisation of major Greenland glaciers, with avalanches of kilometre-size chunks of ice leading to tsunamis and abrupt sea-level rise – complete disintegration of the Greenland Ice Sheet would produce 6-7 metres of sea level rise.
- SRM threatens biodiversity. However the opposite is true. For example refreezing the Arctic will help to preserve wildlife such as polar bears.

Although one could restrict SRM to application in the Arctic only, in order to avoid some of this criticism and acrimony, we have found that more globally applied SRM will almost certainly be necessary for refreezing the Arctic. On closer examination, global SRM could have huge benefits besides refreezing the Arctic, especially as regards sea level rise and reducing flood events.

- Countries like Bangladesh and mega-cities like Calcutta and Shanghai which lie on huge river deltas are already suffering heavily from a combination of sea level rise produced by ocean expansion and tidal surges produced by storms. Both sea level and storm intensity have risen due to global warming; global SRM would reverse these two trends.
- Over a billion people at mid and low latitude rely on meltwater from glaciers and their lives and livelihoods are threatened by glacier retreat. SRM applied at these latitudes would help to save these glaciers and prevent disastrous water shortages.

A basic requirement for planetary restoration will be SRM to reduce the global mean temperature below 0.5C, halt glacier retreat worldwide, and reduce intensity of tropical storms.

Complete planetary restoration, including a halt to sea level rise, is a realistic prospect to benefit future generations by returning the planet to a proven safe state.

Notes and references

[1] Total greenhouse gas positive climate forcing is ~3.0 W/m2 since CO_2 has 2.0 W/m2 and the other GHGs add ~50% to this. But if the negative forcing (particularly from SO_2 aerosol cooling) is included, then the total is much less than 3.0 W/m2. Aerosol cooling is estimated at 1.2 W/m2 but it could be twice or half as much. Here is a chart for the forcing by 2011 as in AR5:
http://www.askaboutireland.ie/_internal/gxml!0/2ocqn930ubywvi8z0wl9dhefnm6z926$3d73c36rjh1e5gr0gbq6qh54hhdyfa

[2] CO_2 has a long lifetime in the atmosphere. But when CO_2 is released into the atmosphere, about a sixth is absorbed by land and a third by sea. Assuming equilibrium when net zero emissions is reached, the CO_2 level will stabilise and the underlying rate of warming, currently 0.25°C per decade, will continue, other things being equal. However if SO_2 aerosol cooling is reduced, e.g. due to the closure of power stations, the rate of warming could actually increase.

[3] Achieving 300 ppm requires the removal of as much CO_2 as caused the level to rise from 280 ppm to the current level. This is more than the legacy CO_2, since about half was absorbed by land and sea, see [2]. The extra CO_2 since it passed 300 ppm in the atmosphere is about 115 ppm (May 2020). Current emissions at 37 $GtCO_2$ per year raise this level by about 2.5%. Thus the required removal could be as much as 40 times 37 $GtCO_2$, or 1.48 trillion tonnes of $GtCO_2$.
https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

[4] Peter Wadhams lists a number of feedbacks in his book "A Farewell to Ice". Positive albedo feedback is generally considered to be dominant.

[5] Stranne et al. do a reverse simulation to show how the Arctic sea ice system can switch from high albedo to lower albedo and back again, in response to the Milankovitch signal.
Arctic Ocean perennial sea ice breakdown during the Early Holocene Insolation Maximum
https://www.sciencedirect.com/science/article/pii/S0277379113004162

[6] During the Younger Dryas the reduced flow of Gulf Stream water towards Europe is thought to have led to much reduced temperatures there, causing ice advance.
https://en.wikipedia.org/wiki/Younger_Dryas

[7] Jennifer Francis points out that, as the Arctic warms faster than the average for the planet, the temperature differential is reduced, thus putting less energy into the Rossby waves which then meander more to north and south. They also tend to get stuck in blocking patterns such as one in the NW Pacific (a "persistent ridge") which is responsible for drought in California.
Dr Jennifer Francis and the Year-Long Blocking Pattern
https://robertscribbler.com/2014/02/26/dr-jennifer-francis-and-the-year-long-blocking-pattern/

[8] The contribution to sea level rise from the Greenland Ice Sheet (GIS) is now greater than the separate contributions from ocean expansion and glacier melt elsewhere.

[9] There is evidence that the disintegration of the Hudson Bay Ice Dome in the early Holocene produced an avalanche of ice blocks which scarred the seabed towards Greenland. Furthermore, huge rocks thrown high up on the Island of Eleuthera in the Bahamas suggest mega-tsunamis arrived there, both in the Eemian and early Holocene, the pressure wave having been reflected off the mid-Atlantic ridge.

Nissen (2015)
Interactive comment on "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming is highly dangerous" by J. Hansen et al.
https://acp.copernicus.org/preprints/15/C5885/2015/acpd-15-C5885-2015.pdf

Model support for forcing of the 8.2 ka event by meltwater from the Hudson Bay ice dome
https://link.springer.com/article/10.1007/s00382-013-1706-z

[10] Plumes of methane bubbles have been observed rising from the seabed in the region of the East Siberian Arctic Sea. Over the past decade these plumes have been growing in size, from a few metres across to the order of a kilometre across.
Understanding the Permafrost–Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf
https://www.mdpi.com/2076-3263/9/6/251/htm

[11] The current atmospheric burden of methane is around 5 gigatonnes, producing around 0.5 W/m2 of climate forcing.

[12] The estimate of 1.0 W/m2 for the climate forcing from Arctic albedo loss since 1979 is based on trends for snow and ice albedo reduction established independently by Flanner and Pistone. The positive albedo feedback started building up in the 80s, resulting in accelerated albedo loss. An unknown factor is the loss of albedo due to the now high proportion of broken ice covered in slush towards the end of summer. Thus the extent and volume of ice may not have decreased since the minimum in 2012, but the albedo could have reduced considerably.

Flanner et al. (2011)
Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008
http://clasp-research.engin.umich.edu/faculty/flanner/content/ppr/FlS11.pdf

Pistone et al. (2014)
Observational determination of albedo decrease caused by vanishing Arctic sea ice
https://www.pnas.org/content/111/9/3322
[13] This again is based on trend analysis. Flanner (see [12]) estimates that total loss of Arctic snow and ice would lead to a 3.3 W/m2 reduction in albedo.

[14] As [1], see diagram: http://www.askaboutireland.ie/_internal/gxml!0/2ocqn930ubywvi8z0wl9dhefnm6z926$3d73c36rjh1e5gr0gbq6qh54hhdyfa

[15] https://en.wikipedia.org/wiki/Global_warming_potential

[16] Obtained by trend analysis, assuming the rate of temperature increase doubles every 40-50 years as concentration and emissions have doubled.

[17] Miller et al (2010) gives AA as 3-4 in 2010.
Arctic amplification: can the past constrain the future?
https://www.geo.umass.edu/faculty/jbg/Pubs/MilleretalQSRPolarAmp2010.pdf

The effect of AA is discussed here, giving AA as between 2 and 4.
https://www.nature.com/articles/s41467-018-05256-8

[18] *Climate crisis: Arctic sea ice freezing at latest date on record*
https://www.independent.co.uk/environment/arctic-sea-ice-siberia-temperature-climate-change-b1723810.html

[19] https://en.wikipedia.org/wiki/Milankovitch_cycles

[20] PIOMAS
http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/

[21] About 93% of the excess heat as a result of global warming is going into the oceans, according to some estimates. This assumption could apply to the Arctic, except that a proportion of that heat has been going into the melting of ice. In some shallow parts of the Arctic Ocean the

seabed has warmed as much as 7°C. There has been increased mixing which takes the heat from surface water, heated when the sea ice recedes, to lower depths.

[22] Stranne et al. (2014), see especially the figures 4 and 5 showing hysteresis and associated values for Milankovitch radiative heating. Once the Arctic is fully switched into a lower-albedo state, with seasonal sea ice instead of perennial ice, this hysteresis needs to be overcome to switch it back.
Arctic Ocean perennial sea ice breakdown during the Early Holocene Insolation Maximum
https://www.sciencedirect.com/science/article/pii/S0277379113004162
https://ars.els-cdn.com/content/image/1-s2.0-S0277379113004162-gr4.jpg
https://ars.els-cdn.com/content/image/1-s2.0-S0277379113004162-gr5.jpg

[23] SAI and MCB can be applied simultaneously without interference because one is in the stratosphere and the other in the troposphere. Different MCB approaches can be applied in different regions, but would interfere if applied in the same region. The emissions of SO2 from the burning of fossil fuel can interfere with MCB.

[24] Latham et al. (2012)
Marine cloud brightening
https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0086

[25] DMS cooling could be particularly advantageous according to this paper:

Kim et al. (2018)
Polar Cooling Effect Due to Increase of Phytoplankton and Dimethyl-Sulfide Emission
https://www.mdpi.com/2073-4433/9/10/384

[26] The 1.5 W/m2 is calculated on the basis that: the average insolation is 360 W/m2; the cloud albedo change through MCB is 0.055; the area of ocean is 361m km2 but only 70% is usable for MCB purposes; and that this usable area is 30% covered with suitable cloud.

[27] Alan Robock makes the claim that SAI alone could refreeze the Arctic
https://register.gotowebinar.com/register/4173973047834427663

[28] Brewer-Dobson circulation means that air from the troposphere enters in the stratosphere from the tropics and leaves at higher latitudes.
https://en.wikipedia.org/wiki/Brewer%E2%80%93Dobson_circulation

[29] Conference session on MEER
MEER: Introduction and conceptual framework
https://ehc.english.ucsb.edu/?page_id=21222

[30] Mitchell et al (2020) preprint
An Estimate of Global, Regional and Seasonal Cirrus Cloud Radiative Effects Contributed by Homogeneous Ice Nucleation
https://acp.copernicus.org/preprints/acp-2020-846/

[31] Ice911 has changed its name to "Arctic Ice Project" and its 'solution' is described in a Wikipedia article
https://www.arcticiceproject.org/blog/2020/9/17/weve-changed-our-name
https://en.wikipedia.org/wiki/Arctic_Ice_Project

[32] Seitz (2010)
Bright Water: Hydrosols, Water Conservation and Climate Change
https://dash.harvard.edu/bitstream/handle/1/4737323/Seitz_BrightWater.pdf

[33] Future directions (2018)
China Bets on Cloud Seeding to Boost Rainfall in Tibet and Xinjiang
https://www.futuredirections.org.au/publication/china-bets-cloud-seeding-boost-rainfall-tibet-xinjiang/

[34] Mitchell et al (2020) preprint
An Estimate of Global, Regional and Seasonal Cirrus Cloud Radiative Effects Contributed by Homogeneous Ice Nucleation
https://acp.copernicus.org/preprints/acp-2020-846/

[35] Desch et al. (2016), see Introduction
Arctic ice management
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000410

[36] Zhou and Flynn (2005)
Geoengineering Downwelling Ocean Currents: A Cost Assessment
http://www.homepages.ed.ac.uk/shs/Climatechange/Carbon%20sequestration/Zhou%20anf%20Flynn.pdf

[37] Desch et al. (2016), see Sections 2 and 3 for details
Arctic ice management
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000410

[38] Ice shield concept
https://envisionation.co.uk/images/iceshieldv4.jpg

[39] Ocean heat pumps have been proposed for energy generation
https://en.wikipedia.org/wiki/Ocean_thermal_energy_conversion

[40] An ice arch formed this year
June 29, 2020 - Ice arch in the Nares Strait
https://modis.gsfc.nasa.gov/gallery/individual.php?db_date=2020-06-29

[41] A proposal was submitted to the Climate Restoration Foundation
https://foundationforclimaterestoration.org/

[42] The contribution from GIS has been accelerating
Contributions to sea-level rise have increased by half since 1993, largely because of Greenland's ice
https://theconversation.com/contributions-to-sea-level-rise-have-increased-by-half-since-1993-largely-because-of-greenlands-ice-79175

[43] There is evidence that the disintegration of the Hudson Bay Ice Dome in the early Holocene produced an avalanche of ice blocks which scarred the seabed towards Greenland. Furthermore, huge rocks thrown high up on the Island of Eleuthera in the Bahamas suggest mega-tsunamis arrived there, both in the Eemian and early Holocene, the pressure wave having been reflected off the mid-Atlantic ridge.

Nissen (2015)
Interactive comment on "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming is highly dangerous" by J. Hansen et al.
https://acp.copernicus.org/preprints/15/C5885/2015/acpd-15-C5885-2015.pdf

Model support for forcing of the 8.2 ka event by meltwater from the Hudson Bay ice dome
https://link.springer.com/article/10.1007/s00382-013-1706-z

[44] Howat et al (2015)
Sudden drainage of a subglacial lake beneath the Greenland Ice Sheet
https://tc.copernicus.org/articles/9/103/2015/tc-9-103-2015.pdf

[45] Landsat image of an ice melange in a fjord in East Greenland.
https://www.researchgate.net/figure/Sikussak-a-frozen-ice-melange-of-multiyear-sea-ice-and-icebergs-Kangerlussuaq-Fjord_fig4_251745698

[46] Wolovick (2018)
Geoengineering polar glaciers to slow sea-level rise
https://www.princeton.edu/news/2018/03/19/wolovick-geoengineering-slow-sea-level-rise-polar-glaciers

[47] Plumes of methane bubbles have been observed rising from the seabed in the region of the East Siberian Arctic Sea. Over the past decade these plumes have been growing in size, from a few metres across to the order of a kilometre across.
Understanding the Permafrost–Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf
https://www.mdpi.com/2076-3263/9/6/251/htm

[48] Extensive methane venting from ESAS
https://www.researchgate.net/publication/41760559_Extensive_Methane_Venting_to_the_Atmosphere_from_Sediments_of_the_East_Siberian_Arctic_Shelf

[49] Zhou and Flynn (2005)
Geoengineering Downwelling Ocean Currents: A Cost Assessment
http://www.homepages.ed.ac.uk/shs/Climatechange/Carbon%20sequestration/Zhou%20anf%20Flynn.pdf

[50] Pohlman et al. (2017) show that micronutrients lifted by methane bubbles stimulate phytoplankton, with an uptake of CO2 sufficient to more than counter the global warming effect of the methane. The phytoplankton are food for the methanotrophs in the water column which help digest the methane as it rises, so relatively few bubbles reach the surface.
Enhanced CO2 uptake at a shallow Arctic Ocean seep field overwhelms the positive warming potential of emitted methane
https://www.pnas.org/content/early/2017/05/02/1618926114

[51] Renaud de Richter et al (2019)
Iron Salt Aerosol: a natural method to remove methane and other greenhouse gases
https://www.researchgate.net/publication/335919987_Iron-Salt-Aerosol-Method_IMechE_11-Sept-19