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Key Points:

- To prevent strong positive feedbacks in the climate system, it may be necessary to artificially increase sea ice thickness in the Arctic
- We calculate that 1.4 m of seawater pumped to the surface freezes more readily and increases ice thickness by 1.0 m in one winter
- We describe a method employing devices using wind power to pump water and thicken ice, and discuss the feasibility and effectiveness of deploying such devices over the Arctic

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Arctic ice management

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Abstract As the Earth's climate has changed, Arctic sea ice extent has decreased drastically. It is likely that the late-summer Arctic will be ice-free as soon as the 2030s. This loss of sea ice represents one of the most severe positive feedbacks in the climate system, as sunlight that would otherwise be reflected by sea ice is absorbed by open ocean. It is unlikely that CO_2 levels and mean temperatures can be decreased in time to prevent this loss, so restoring sea ice artificially is an imperative. 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 multipronged strategy for restoring sea ice and arresting the strongest feedbacks in the climate system.

1. Introduction

1.1. The Urgent Need to Deal with Climate Change

The climate is warming, and the rate of change is highest in the Arctic, where summer ice is vanishing at an accelerating rate. According to the 2013 Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the warming of the atmosphere and ocean system is unequivocal. From 1880 to 2012 the globally averaged combined land and ocean surface temperatures increased $0.85 \pm 0.20°C$, with the last three decades warmer than the previous one and warmer than any others since 1850. The increase in temperatures has been even higher in the Arctic region, with dramatic effects. On 30 December 2015, temperatures on a buoy 300 km from the North Pole shot up 29°C due to an influx of warm air from Storm Frank, and some data suggested the temperatures topped the freezing point at the North Pole in the dead of winter, an exceedingly rare event (http://www.telegraph.co.uk/news/weather/12075282/North-Pole-temperatures-spike-above-freezing-as-Storm-Frank-sends-warm-air-north.html, 10 Jul. 2016).

It can be stated with "high confidence" (see AR5 for a definition of this and similar terms) that the Greenland and Antarctic ice sheets have been losing mass and glaciers have been shrinking worldwide. Arctic sea-ice extent (area covered by at least 15% ice) decreased from 1979 (when satellite measurements began) to 2012, at a rate "very likely" in the range of 3.5%–4.1% per decade. The pace of decrease is apparently accelerating: for the baseline 1978–1999, the rate was 3% per decade [*Johannessen et al*., 1999]. The loss of Arctic sea ice in the summer of 2007 was much greater than expected and attracted the attention of the scientific community and the public [*Kerr*, 2007; *Revkin*, 2007]; but the extent of sea ice in 2012 was even lower, and through July 2016, the sea ice extent was lower than ever recorded in the spring, more than 2 standard deviations below the 1981–2010 average. Figure 1 illustrates the alarming and accelerating loss of ice in the Arctic Ocean.

The loss of Arctic sea ice is due to anthropogenic effects and is therefore likely to continue to accelerate. According to the IPCC AR5 Report, the increase in global temperatures is very similar to that predicted from the cumulative anthropogenic CO_2 emissions of 2040 ± 310 Gt between 1750 and 2011. It is "extremely likely" that most of the global temperature increases are due to anthropogenic forcings. Anthropogenic

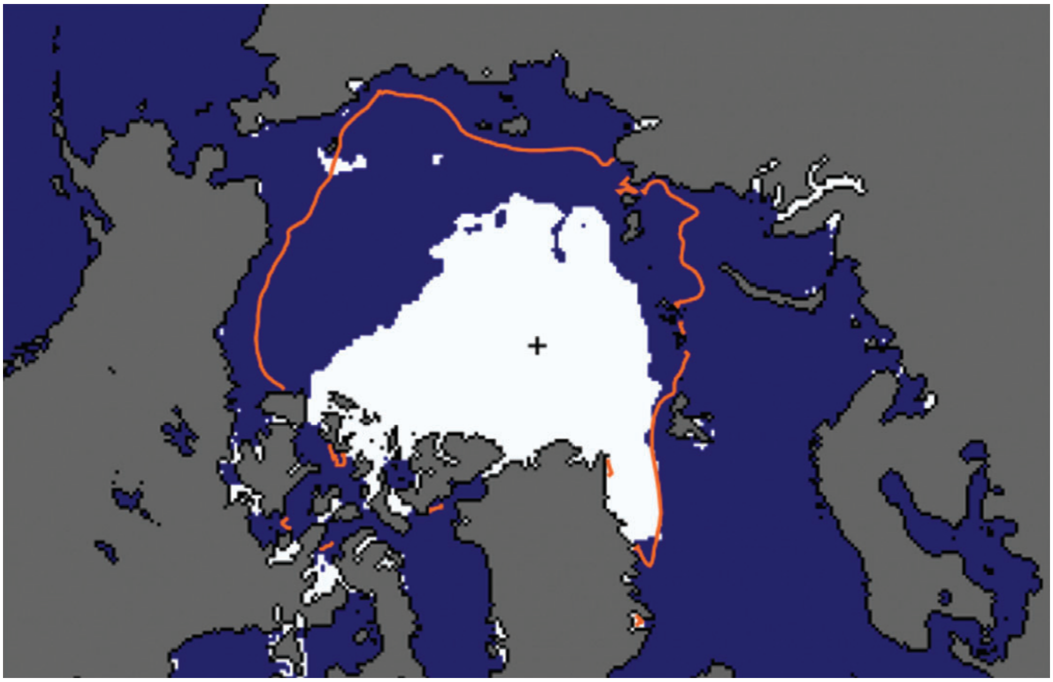

Figure 1. Arctic sea-ice extent (area covered at least 15% by sea ice) in September 2007 (white area). The red curve denotes the 1981–2010 average. Sea-ice extent in 2016 was the second lowest ever recorded. Courtesy of the National Snow and Ice Data Center (http://nsidc.org/arcticseaicenews/charctic-interactive-sea-ice-graph/).

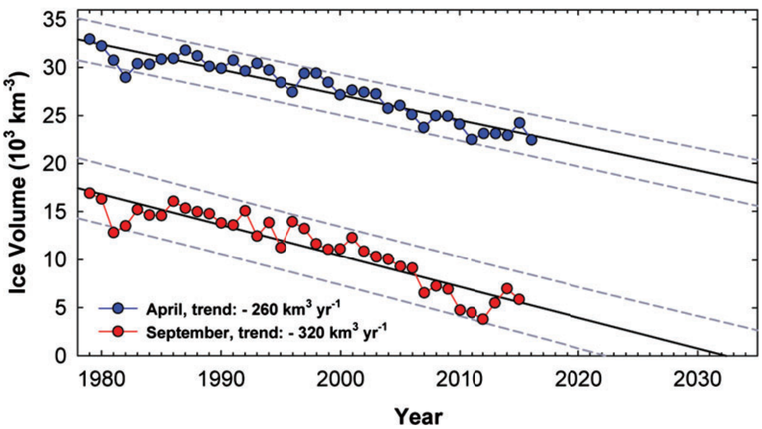

Figure 2. Monthly average Arctic sea-ice volume for April and September. Linear fits suggest sea-ice volume at the end of Arctic summer is decreasing by 320 km^3 per year and will vanish by the early 2030s or sooner. Data courtesy of PIOMAS (http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/).

influences have "very likely" contributed to Arctic sea-ice loss since 1979. Global average temperatures have been observed to rise linearly with cumulative CO_2 emissions and are predicted to continue to do so, resulting in temperature increases of perhaps 3°C or more by the end of the century. The Arctic region will continue to warm more rapidly than the global mean. Year-round reductions in Arctic sea ice are projected in virtually all scenarios, and a nearly ice-free (<10^6 km^2 sea-ice extent for five consecutive years) Arctic Ocean is considered "likely" by 2050 in a business-as-usual scenario.

While the trends in sea-ice extent are consistent with late-summer ice vanishing from the Arctic Ocean by mid-century, the trends in sea-ice volume and sea-ice thickness seem more consistent with attainment of such a state even sooner. Figure 2 shows the minimum volume of Arctic sea ice through 2016, as similarly presented by *Schweiger et al*. [2011], using data from the Pan-Arctic Ice Ocean Modeling and Assimilation

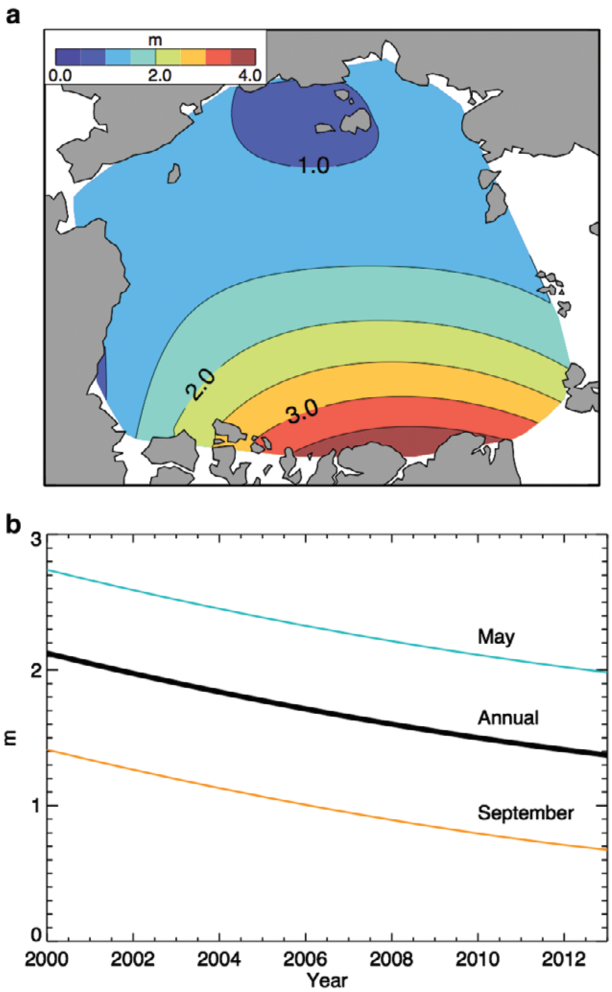

Figure 3. (a) Mean annual thickness of ice in the Arctic over the period 2000–2012, as determined by a combination of datasets using different sensing techniques, from *Lindsay and Schweiger* [2015]. (b) The mean thickness over the Arctic of the ice in May, September, and averaged throughout the year. The annual average is decreasing at 0.58 m per decade, and a simple extrapolation suggests an ice-free Arctic in summer by the 2030s. Figure taken from *Lindsay and Schweiger* [2015] "Arctic sea ice thickness determined using subsurface, aircraft, and satellite observations," *The Cryosphere* 9, 269–283. Used with permission from R. Lindsay.

System [PIOMAS; *Zhang and Rothrock*, 2003]. Before 2007, sea-ice volume was never known to drop below 9000 km^3, but sea-ice volume has dropped below 7000 km^3 every year since then. A linear extrapolation suggests the late-summer Arctic ice volume is decreasing by 3200 km^3 per decade and will certainly vanish by the 2030s. Some studies indicate the ice may effectively vanish even sooner than these estimates, possibly before 2020 [*Maslowsky et al.*, 2012; *Wadhams*, 2016].

Sea-ice volume is decreasing at a faster rate than sea-ice extent because the ice is getting thinner over time. Newly created "first-year" ice is typically not more than 1 m thick. Ice that survives the summer can grow and become multiyear ice, with a typical thickness of 2–4 m. During the 1980s, multiyear ice comprised 50%-60% of all ice in the Arctic Ocean, but by 2010 only 15% of Arctic sea ice was over 2 years old [*Comiso*, 2012; *Polyakov et al.*, 2012]. First-year ice is much more susceptible to summer melting and to fracturing and dispersal by winds and waves. Warmer summers hinder the survival of ice through to the next winter and inhibit formation of multiyear ice. Figure 3 shows the mean annual thickness of sea ice in the Arctic for the period 2000–2012, as determined by combining multiple datasets using various techniques such as upward-looking sonar, electromagnetic sensors, LIDAR, or radar altimeters, etc. [*Lindsay and Schweiger*, 2015]. Significantly, half the Arctic Ocean is characterized by ice that is less than 1.5 m in thickness on average; an increase of even 1 m would be significant. Over this period, the mean annual ice thickness decreased at a rate of 0.58 m per decade. A simple linear extrapolation of the data suggests an ice-free Arctic in September as soon as the late 2020s, or earlier than that if the trends accelerate.

The Arctic is warming faster than the rest of the planet because of several polar amplification feedbacks [*Holland and Bitz*, 2003; *Alexeev and Jackson*, 2013; *Pithan and Mauritsen*, 2014], chief among them is the strong ice-albedo feedback. Fresh snow reflects up to 90% of incident sunlight, sea ice reflects sunlight with albedo up to 0.7, and even sea ice with melt pools has albedo 0.2–0.6 (see Section 2.3); in contrast, open water absorbs most sunlight, having an albedo close to 0.06 (https://nsidc.org/cryosphere/seaice/processes/albedo.html, 10 Jul. 2016). As ice melts, it becomes open water capable of absorbing more sunlight, in a positive feedback. On long (10^4–10^5 year) timescales, this ice-albedo feedback is what amplifies the external forcing due to changes in Earth's obliquity and eccentricity (Milankovitch cycles) into the large temperature variations that drive ice ages [*McGehee and Lehman*, 2012]. But the feedback can act on shorter timescales, and there is direct evidence that the ice-albedo feedback enhanced the loss of ice during the 2007 Arctic summer [*Lindsay et al.*, 2009; *Perovich et al.*, 2008].

A simple calculation underscores the important role played by Arctic ice in Earth's climate. The Arctic acts as a major temperature regulator for the Earth [*Winton*, 2006]. During the summer months, Arctic sea ice historically has covered an area close to 6 million km^2 (Figure 1). On average it receives sunlight for half the year, with the Sun $\approx 10°$ above the horizon. Total cloud cover over the ocean during the summer months averages 82% [*Eastman and Warren*, 2010]. Thus the surface in 1 year absorbs a total energy $(6 \times 10^{12}\ \mathrm{m}^2) \times (1366\ \mathrm{W\ m}^{-2}) \times (\sin\ 10°) \times (0.18) \times (0.5\ \mathrm{year}) \times (1-a)$, where a is the albedo. Assuming $a = 0.06$ for ocean water and $a = 0.75$ for sea ice, the difference in energy absorbed is 2.8×10^{21} J in a year. Averaged over 1 year and the total area of the Earth, $4\pi R_E{}^2 = 5.12 \times 10^{14}\ \mathrm{m}^2$, this is equivalent to $0.17\ \mathrm{W\ m}^{-2}$ of radiative forcing. The current climate change is driven by about $1.2\ \mathrm{W\ m}^{-2}$ of anthropogenic radiative forcing, so losing summer sea ice would have a profound effect on Earth's climate, accelerating temperature increases. Conversely, *preventing* the loss of Arctic ice that will inevitably arise from climate change (or even increasing the amount of Arctic ice) would have a measurable impact on slowing temperature increases worldwide.

This argument is bolstered by consideration of other feedbacks unique to the Arctic. Billions of metric tons of carbon are stored in the permafrost of the tundra and would be released as CH_4 or CO_2 if the permafrost were to melt [*Dutta et al*., 2006; *Walter et al*., 2006; *Schuur et al*., 2008]. Already the rate of carbon release from thawing permafrost appears to be increasing [*Schuur et al*., 2008]. According to the IPCC AR5, it is virtually certain that near-surface (uppermost 3.5 m) permafrost extent at high northern latitudes will be reduced as global mean surface temperatures increase. The area of permafrost is projected to decrease by 81% in a business-as-usual model (RCP8.5). The threat from methane emitted from the melting of offshore permafrost in the shelf seas of the Arctic may be even greater [*Shakhova et al*., 2014; *Wadhams*, 2016]. Release of billions of tons of the greenhouse gases CH_4 or CO_2 over a few decades would substantially increase Earth's mean surface temperatures further.

Other consequences of Arctic sea ice loss are severe. Decreasing sea ice may be altering weather patterns in the northern hemisphere by weakening the jet stream [*Cassano et al*., 2014; *Overland et al*., 2015]. Decreased sea ice in the Arctic also seems to have caused enhanced coastal erosion [*Overeem et al*., 2011]. Loss of sea ice threatens the entire sea-ice ecosystem [*Post et al*., 2013], including, among other things, making it more difficult for polar bears to find food [*Derocher et al*., 2004].

For the preservation of the Arctic and its unique ecosystems, and especially to preserve its role in Earth's climate through the ice-albedo feedback, and to prevent the worst positive feedbacks such as release of gigatons of greenhouse gases stored in the permafrost, it is vital to do as much as possible to prevent loss of sea-ice in the Arctic. Moreover, the need is *urgent*, as the normal cooling effects of summer sea ice are already lessened and may disappear in less than two decades.

1.2. Dealing with a Changing Arctic

Since Arctic sea ice loss is predominantly anthropogenic in origin, the logically simplest way to restore the ice is to refrain from engaging in the activities that have increased mean surface temperatures. In other words, solving the global climate change problem would largely solve the problem of Arctic sea ice loss. As a practical matter, this is not a solution, as political efforts to decrease CO_2 emissions and other human activities have proved ineffective. Also even if anthropogenic forcings on the global climate such as CO_2 emissions were to abate, this would not change the current trends in mean temperature for the next several decades, too late to prevent loss of summer sea ice in the 2030s. Restoring Arctic sea ice thus probably requires a local solution tailored to that part of the climate system. Happily, though, any prevention of Arctic sea ice loss has the advantage of arresting the most powerful feedback in the climate system and making the global climate change easier to deal with.

Efforts to purposefully alter the climate are often labeled "geoengineering," to distinguish such actions from the dominant mode of human activity, which is alteration of the climate without purpose. The term "geoengineering" is used pejoratively by those who feel it is morally irresponsible to try to alter the climate system in an attempt to prevent ecological disasters, mass extinctions, and human misery brought on by displacement, famine, and war. It is argued that our knowledge of the climate system is imperfect; that lessening the effects of climate change in one area (e.g., temperature increases) does not fix the problem in other areas (e.g., precipitation patterns, ocean acidification); that the only solution to all these problems is a rapid reduction in CO_2 and other greenhouse gas emissions; that actively working to improve the climate presents a moral hazard, as producers of CO_2 emissions will feel less pressure to work toward a solution; and that assuming an active role in the climate commits us morally and practically to a permanent role in the climate [*Lin*, 2013; *Committee on Emerging Research Questions in the Arctic*, *Polar Research Board*, *and Division on Earth and Life Studies*, 2014; *Committee on Geoengineering Climate*: *Technical Evaluation and Discussion of Impacts*, *Board on Atmospheric Sciences and Climate*, *Ocean Studies Board*, *Division on Earth and Life Studies*, *National Research Council*, 2015a, 2015b]. All these arguments are valid, and perhaps stewardship of the Earth's climate is not a responsibility to be desired; but again, the alternative is to continue altering the climate without any purpose or plan. We prefer the term "geodesign" (A. Anbar, personal communication, 2016), in recognition of the fact that the climate is a highly integrated system that may be impossible to "fix" simply through application of a technology, yet which might be improved by viewing the climate as a planetary system, accepting the role of humans in the climate, and designing a new role for humans in the climate.

Although technological innovation by itself will not solve all the challenges of climate change and Arctic sea ice loss — there is no silver bullet technological solution to all the problems of climate change — it is also the case that humans cannot make a difference in these problems without the tools to effect change. In the geoengineering literature, two techniques dominate the discussion: carbon capture and sequestration (CCS) and solar radiation management (SRM). These proposed techniques were reviewed by the Committee on Geoengineering Climate, who argued that no technique is completely effective or risk-free. CCS has the potential to directly counteract the rise of CO_2 that is the primary driver of climate change, and is necessarily a global solution; but capturing CO_2 at a cost much less than the revenue created by generating the CO_2, and stably sequestering the captured CO_2 are currently unsolved problems [*Committee on Geoengineering Climate*: *Technical Evaluation and Discussion of Impacts*, *Board on Atmospheric Sciences and Climate*, *Ocean Studies Board*, *Division on Earth and Life Studies*, *National Research Council*, 2015a; http://www.nap.edu/catalog.php?record_id=18805]. It is also the case that CCS would act on decades-long timescales, which may be too late to save Arctic sea ice and prevent strong detrimental feedbacks on the climate. In contrast, altering the albedo of the Earth through SRM would act on timescales of years only [*Committee on Geoengineering Climate*: *Technical Evaluation and Discussion of Impacts*, *Board on Atmospheric Sciences and Climate*, *Ocean Studies Board*, *Division on Earth and Life Studies*, *National Research Council*, 2015b; http://www.nap.edu/catalog.php?record_id=18988], but suggested SRM mechanisms such as injection of sulfate aerosols into the stratosphere, or brightening of marine clouds by production of cloud condensation nuclei, introduce their own risks such as alteration of precipitation patterns and alteration of ocean chemistry. The Committee on Geoengineering Climate argues that a basket of techniques may be more effective and less risky than any single technique.

Geoengineering of the Arctic in particular, because of its vital role in Earth's climate, has been proposed before [*Flannery et al*., 1997; *Lane et al*., 2007; *Caldeira and Wood*, 2008; *Robock et al*., 2008; *Egede-Nissen and Venema*, 2009; *MacCracken et al*., 2013; *Tilmes et al*., 2014]. *Lane et al*. [2007] and *Caldeira and Wood* [2008] in particular investigated the effects of shading just the high-latitude regions near the North Pole, by a sunshade of aerosols. *Caldeira and Wood* [2008] concluded that a 21% decrease in insolation north of 71°N would allow ice to survive in a world with a double today's CO_2 in the atmosphere. The annual cost of injecting the required levels of aerosols would be on the order of tens of billions of dollars [*Robock et al*., 2009; see also *Keith and Dowlatabadi*, 1992; *Keith*, 2000; *Barrett*, 2008]. Thus, a powerful tool for altering climate could be had at a price affordable by governments. Injection of aerosols comes with a host of problems, though, including possible disruption of monsoon patterns in the southern hemisphere [*Robock et al*., 2008] and detrimental effects on the ozone layer if SO_2 is used as the aerosol [*Rasch et al*., 2008; *Tilmes et al*., 2008]. The most commonly considered tools are therefore insufficient to the task. CCS methods, if they were to become affordable and effective, would take decades to modify the climate, probably after the Arctic becomes incapable of creating summer sea ice in the 2030s, by which point the worst feedbacks will have set in. SRM by aerosol injection is affordable and immediately available and would effectively lower temperature, but at the cost of a panoply of detrimental side effects. Intervention in the Arctic is called for, but a more effective tool is needed.

The ideal tool would simply restore the summer sea ice extent in the Arctic. In a sense, this could be considered a SRM strategy, since preventing sea ice loss would prevent a decrease in albedo. Potentially the same technique could be used to increase summer sea ice and therefore increase the albedo in the Arctic, but the primary goal is to restore the Arctic sea ice to its state before anthropogenic climate change. We label this Arctic ice management (AIM).

1.3. Arctic Ice Management

Increasing Arctic summer sea ice can be accomplished in two ways: either the sunlight that melts the ice in the summer can be reduced, or more ice can be created over the Arctic winter. Sulfate aerosols would effectively block sunlight [*Caldeira and Wood*, 2008], but with considerable negative side effects; a more environmentally benign mechanism would seem to be the technique of marine cloud brightening, by which cloud cover is increased by introduction of cloud condensation nuclei into the lower atmosphere [*Latham*, 1990]. We consider this a promising mechanism worthy of future study, and return to this idea in Section 4; but our focus here is on enhancing sea ice generation over the winter.

A simple mechanical method for increasing winter ice, suggested by Flannery *et al.* [1997], is the mechanical pumping or spraying of seawater to the top surface of the ice, which would allow the ocean's heat to radiate to space, bypassing the insulating effects of the ice sheet. Unlike other SRM methods, thickening sea ice is attractive because it merely enhances a naturally ongoing process in the Arctic. The idea originally was presented as one in a large number of potential geoengineering proposals, and even though other (CCS and SRM) geoengineering ideas have seen some development, apparently no studies followed up on this suggestion. The implied scale of the technique (production of ice over millions of square kilometers) may have discouraged further investigation. A similar idea was echoed in a recent study made by *Frieler et al*. [2016], who examined what it would take to prevent sea level rise by pumping seawater to the middle of the Antarctic continent, where it would freeze. They concluded that the water would have to be pumped 700 km inland, requiring wind farms generating approximately 1300 GW of power, or 7% of current world energy production (or possibly double that amount). After that estimate, the authors did not bother to estimate a cost or implementation strategy. Whatever the reason for neglecting the study of pumping seawater to thicken Arctic sea ice, we consider the idea to be worthy of future study. (We note that Sev Clarke also has suggested building "Ice Shields" by having wind-pumped seawater brought to the surface to freeze, adding to a growing lens of ice. He proposes building ice structures for roads and to capture and transport seafloor methane, but recognized the potential to reflect sunlight as well. http://envisionation.co.uk/index.php/sev-clarke/climate-engineering-resource-page 27 December, 2016.)

1.4. AIM by Wind-Driven Pumping of Seawater

In this paper, we explore a method for mechanically creating more ice over the Arctic winter. In Section 2 we present a model relating the time-varying thickness of Arctic sea ice as a function of simple input parameters. We calculate how much the thickness of ice can be increased by pumping seawater to the surface at various rates. We calculate the rate of melting of sea ice in the summer, and we estimate the ability of artificially thickening the ice to counteract global warming trends. In Section 3, we describe a machine that could be built to accomplish bringing seawater to the surface using a wind-driven pump. We estimate the costs to construct and deploy these devices. In Section 4 we discuss some possible implications and suggest directions for future study and discussion. We hope that this paper spurs further thinking about AIM to prevent a strong and detrimental positive feedback in the climate system.

2. AIM Using Wind-Powered Pumps

2.1. Freezing of Ice over the Arctic Winter

To constrain the ability of mechanical devices to thicken Arctic sea ice, it is first necessary to have a model of how seawater freezes. Here we derive such a model, similar in spirit to the pioneering work of *Maykut and Untersteiner* [1971]. Seawater in the Arctic Ocean typically starts to freeze in September, when insolation ceases and the surface temperature stays below −1.8°C (271 K), the freezing point of water with ocean-level salinity near 35 parts per thousand (ppt). (Salinity varies from 32 to 37 ppt, and each 5 ppt of extra salinity depresses the freezing point by 0.28°C.) The first ice crystals to form on the surface agglomerate into a slush known as frazil. As freezing continues, the ice thickens and becomes fresher. If pockets of liquid brine are trapped in the ice, they will slowly migrate downward, depressing the melting point of the ice the brine is in contact with, eventually reaching the ocean at the base of the ice. This leaves long thin trails in the ice that cause the mechanical properties of the ice to change. Snow may also cover the sheet of ice.

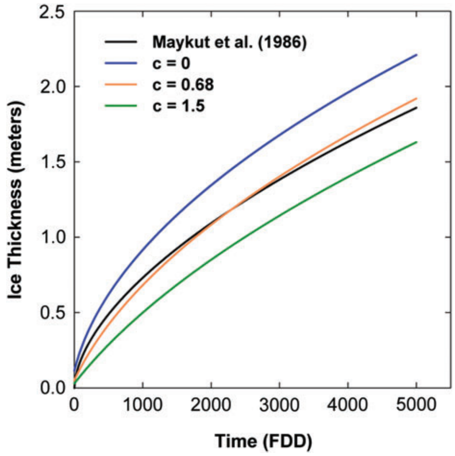

Figure 4. Winter Arctic ice thickness as a function of FDD (see text for definition). The black curve is the empirical fit from *Maykut* [1986]. The other curves are results from our first-principles model using three different assumptions about snow cover (parameterized by *c*; see text). The orange curve ($c = 0.68$) is our best fit to the empirical data and corresponds to a thin (time average ~8 mm) layer of snow on the ice.

Because the surface temperatures in the Arctic winter drop to −35°C to −40°C on average, the ice is very cold, and seawater in contact with the ice can continue to freeze, but only if the latent heat of fusion can be carried away from the bottom of the ice to the cold surface. From the surface the heat can be carried away by wind or radiated to free space. If the heat flux through the ice, F, is known, then the rate at which the ice thickness, x, changes is easily found, since

$$F = \rho_i l_i \frac{\mathrm{d}x}{\mathrm{d}t},$$

where $\rho_\mathrm{i} = 917\,\mathrm{kg\,m^{-3}}$ is the ice density, and $l_i = 3.32 \times 10^5\,\mathrm{J\,kg^{-1}}$ is the latent heat of fusion. The heat flux is carried through the ice by conduction, and so is related to the temperature gradient across the ice:

$$F = k\,(x)\,\frac{\mathrm{d}T}{\mathrm{d}x},$$

where $k(x)$ is the thermal conductivity and is a function of the ice thickness, x. Following *Trodahl et al*. [2001], we assume $k(x) = k_i = 2\,\mathrm{W\,m^{-1}\,K^{-1}}$ if $x > x_0 = 0.5\,\mathrm{m}$, but for $x < x_0$, $k(x) = k_i\,[1 + x/x_0\,]/2$, accounting for the fact that ice near the surface is more porous and less conductive. We also assume a thin layer of snow with relatively low thermal conductivity k_s and thickness d, on top of the ice. Above the snow, the temperature is the ambient surface temperature, which is ΔT degrees colder than the base of the ice, which is at −1.8°C. Integrating between the surface and the base of the ice, we solve for the flux F, as a function of x. We then relate $\mathrm{d}x/\mathrm{d}t$ to x, and then integrate to find x as a function of $(\Delta T)\,t$. This product is related to the commonly used quantity known as freezing degree days, or FDDs. Each day spent below freezing, the FDDs are augmented by the number of degrees celsius the surface is below freezing:

$$\mathrm{FDD} = \int_0^t \left(T_\mathrm{frz} - T_\mathrm{surf}\right)\mathrm{d}t$$

where $T_\mathrm{frz} = -1.8°\mathrm{C}$, and t is measured in days. In our derivation, there is one unknown quantity, the product of the snow's thermal conductivity and its thickness, which we parameterize by $c = (k_i\,d)/(k_s\,x_0)$. We set this to $c = 0.68$, equivalent to a snow thermal conductivity $k_s = 0.045\,\mathrm{W\,m^{-1}\,K^{-1}}$ [*Pomeroy and Brun*, 2001] and (time-averaged) thickness $d = 8\,\mathrm{mm}$. We choose this value to match our derived $x(t)$ to an empirical formula found by *Maykut* [1986]:

$$x\,(\mathrm{FDD}) = 0.0133\ \ (\mathrm{FDD})^{0.58}\,m$$

In Appendix A we solve the above formulas. The results are displayed in Figure 4. For the optimal value of $c = 0.68$, deriving the following formula (for $x > x_0$):

$$x\,(\mathrm{FDD}) = -0.533\ +\ 0.5\left[\frac{\mathrm{FDD}}{221.2} + 1.364\right]^{1/2}\ \mathrm{m}$$

For $100 < \mathrm{FDD} < 5000$ (a typical value at the end of the Arctic winter), our formula predicts the thickness of ice in the Arctic to within 10%. Both formulas predict that at the end of Arctic winter, if FDD = 5000, about 1.92 m of ice should grow.

2.2. Thickening Arctic Ice with Pumping

Water pumped directly to the surface can freeze more rapidly, because the latent heat of fusion can immediately be lost to the atmosphere or space. Pumping 1 m of water to the surface will result in the ice being thicker by a substantial fraction of 1 m, although two effects prevent the ice from thickening by exactly the amount that is pumped. First, the latent heat released at the surface potentially could raise the surface temperature, effectively reducing the number of FDDs experienced by the ice sheet. Second, as the ice sheet thickens from above, it makes it more difficult for the heat released by ice freezing at the ice–ocean interface to reach the surface.

We first consider the effect of the release of heat at the surface, which could raise the surface temperature. In the calculation above, we assumed that the surface temperature equaled the temperature of the air. We could instead have calculated the surface temperature directly: the ice surface will attain a temperature balancing heating by release of latent heat of fusion (at the base of the ice layer, due to normal freezing, as well as the top of the ice layer, due to freezing of pumped water) against the cooling due to radiation and contact with the air:

$$\varepsilon \sigma T^4 + h\left(T_{\mathrm{air}} - T\right) = \rho_i l_i \left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)_{\mathrm{pump}} + k\left(T_{\mathrm{frz}} - T\right),$$

where T is the surface temperature, ε is the fraction of the outgoing long radiation that is transmitted through the Arctic clouds (we assume $\varepsilon = 0.18$), $h = 30\ \mathrm{W\,m^{-2}\,K^{-1}}$ is a typical heat transfer coefficient (see below), $T_{\mathrm{frz}} = -1.8°\mathrm{C}$, and k is the *average* thermal conductivity through the ice (see Appendix A). The rate at which ice would be added to the surface by pumping is $(\mathrm{d}x/\mathrm{d}t)_{\mathrm{pump}}$. For the case $(\mathrm{d}x/\mathrm{d}t)_{\mathrm{pump}} = 0$, we would derive a surface temperature that is 0.7°C warmer than the air temperature. Under typical conditions, roughly half the heat released from freezing water is lost by radiation, and half by contact with cold air. If we repeat the calculation assuming enough water is pumped to produce 3 m of ice over the Arctic winter, we would find under typical conditions that the surface temperature exceeds the air temperature by 2.1°C. Direct losses by radiation are little changed, but the loss of heat to the air is tripled. Ultimately, though the change in surface temperature is slight.

An additional consideration is the blanketing effect of the extra ice, which impedes the loss of heat released as seawater freezes on the underside of the ice. The formula relating heat flux F to the temperature difference ΔT and the ice thickness x remains the same as before (Appendix A), but the equation for the ice thickness is altered to account for the water pumped to the surface:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)_{\mathrm{pump}} + \frac{F}{\rho_i l_i},$$

where again $(\mathrm{d}x/\mathrm{d}t)_{\mathrm{pump}}$ is the rate at which ice is added to the top of the ice sheet by pumping. The solution must be found numerically. We do so by balancing the heating and cooling terms at the surface to solve for the surface temperature, T_{surf}. Once T_{surf} is found, the flux F through the ice and the rate of increase of the ice thickness, $\mathrm{d}x/\mathrm{d}t$, are readily found and integrated.

If pumping moves enough water to the surface to add a thickness $\Delta x = (\mathrm{d}x/\mathrm{d}t)_{\mathrm{pump}}$ (6 mos) to the ice over the Arctic winter, we find as a general result that energetics of the system limit the increase in the ice thickness above the no-pumping case to about 0.7 Δx. For example, without pumping, the ice grows to thickness of 1.92 m after 5000 FDDs. If pumping moves enough water to add thickness $\Delta x = 1$ m, we find the ice thickness at the end of the winter is 2.61 m, an increase of 0.69 m. For $\Delta x = 2$ m, the thickness at the end of winter is 3.36 m, an increase of 1.44 m; and for $\Delta x = 3$ m, the final ice thickness is 4.16 m, an increase of 2.24 m. The relation that the ice thickness increases by $\approx$0.7 Δx holds roughly ($\pm$10%) across the range of relevant FDDs seen by the Arctic. Pumping has the effect of increasing the surface temperature (due to latent heat released as water freezes on the surface), resulting in an increase in heat losses to the air. On the other hand, as the ice is thicker, the flux of heat from water freezing at the bottom of the ice is lower. The two effects combine to add about 0.7 Δx to the ice thickness.

In summary, pumping water to the surface is a viable means of adding to the thickness of the ice over the Arctic winter. For a typical Arctic location that would experience 5000 FDDs, the ice would normally freeze to a thickness of about 2 m over the winter. Pumping at a rate $(\mathrm{d}x/\mathrm{d}t)_{\mathrm{pump}}$ over the Arctic winter, raising enough water to add to the ice thickness by Δx, will increase the thickness of the ice above the natural increase; however, the latent heat released at the surface will limit the increase to about 0.7 Δx. Nevertheless, this is a significant amount. In our discussion of wind-powered pumps we adopt $\Delta x \approx 1.4$ m as a baseline (requiring pumping of 1.3 m of water), which implies that wind-powered pumping can increase the thickness of the ice by about 1.0 m beyond what it would normally attain.

2.3. Melting of Ice in the Arctic Summer

With the right equipment, it is possible to produce extra ice in the Arctic winter, but the presence of this ice will help the ice-albedo feedback only if it persists through the summer months, so that the ice can reflect sunlight. We anticipate that production of ice will be more cost-effective in certain regions than in others: extra ice produced too far south will melt too quickly in the summer to make a difference, while in other regions ice may naturally survive the Arctic summer anyway. We must therefore calculate the rate at which the ice sheet melts as a function of its location during the Arctic summer, to quantify the effect of adding ice during the winter months and to determine where such an action will have the greatest effect. Here we present a first-principles model for the decrease in ice thickness due to summer ice melting, benchmarking it against ice thickness and meteorological data.

To calculate the summer melting of ice, we construct a model including heating of the ice by insolation and contact with warm air. After every time interval Δt, the thickness of the ice decreases by an amount Δx, where

$$\Delta x = -\frac{\Delta t}{\rho_{\rm ice} l_{\rm ice}} \left[S\ (1-a) \left(1-f\right) + h\ (T - 273\ \mathrm{K}) \right],$$

where S is the insolation, a the albedo, f the cloud cover, and h is a heat transfer coefficient. As before, $\rho_i = 917\ \mathrm{kg\ m^{-3}}$ is the ice density, and $l_i = 3.32 \times 10^5\ \mathrm{J\ kg^{-1}}$ is the latent heat of fusion. We take

$$S = 1366\ \left[\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\ \mathrm{HA}\right]\ \mathrm{W\ m^{-2}},$$

where φ is the local latitude (75° at the average location of the buoy), the Sun's declination is $\delta = 23.44°$ $\sin\left(2\pi\ (t - t_0)/365.25\ \mathrm{d}\right)$, where t_0 refers to the vernal equinox, and $\mathrm{HA} = 2\pi\ (\mathrm{t} - 12\ \mathrm{h})/(24\ \mathrm{h})$ is the hour angle (equal to zero at noon). If this formula returns a negative insolation, $S = 0$ is assumed. Both albedo and cloud cover can vary with location and time of year. Generally, the albedo is characteristic of ice or snow, $a = 0.75$, at the beginning of the summer, switching to a much lower albedo in the range 0.2–0.6 at the end of the summer, as melt pools like that depicted in Figure 5 develop [*Agarwal et al.*, 2011]. The transition apparently occurs at this location after 15 TDDs (roughly 29 June), and we let the late-summer albedo be a free parameter in our model. As for the cloud fraction, the Cloud-Aerosol Lidar with Orthogonal Polarization sensor in the Afternoon Constellation of Earth-observing satellites indicates that the a typical cloud fraction for regions of the Arctic with over 90% ice coverage is $f = 0.832$ [*Chan and Comiso*, 2013].

Figure 5. Melt pools on melting sea-ice (courtesy of NASA, retrieved from https://en.wikipedia.org/wiki/Melt_pond#/media/File:Ponds_on_the_Ocean,_ICESCAPE.jpg).

The heat transfer coefficient depends on the wind speed and is taken to be:

$$h = 10.45 - V + 10\ V^{1/2}\ \mathrm{W\ m^{-2}\ K^{-1}}$$

where V is the average wind speed, in m/s, valid for $2\ \mathrm{m\ s^{-1}} < V < 20\ \mathrm{m\ s^{-1}}$ [*Osczevski*, 1995]. If $T < 273\ \mathrm{K}$, this term is assumed to vanish. While wind speed data are lacking at the specific position of the buoy, the typical wind speed in the Arctic summer is $5\ \mathrm{m\ s^{-1}}$ [*Kalnay et al.*, 1996]. For $V = 5\ \mathrm{m\ s^{-1}}$, $h = 27.1$, and h varies from this value by only 10% over the range $3–8\ \mathrm{m\ s^{-1}}$. Temperature data from the buoy are available at 2-hour intervals.

Because we wish to focus on regions where ice persistence is marginal, we benchmark against data from ice mass balance (IMB) buoy (ID code: 30106) deployed in April 2007 by the Sea-Ice Experiment – Dynamic Nature of the Arctic (SEDNA) campaign in the Beaufort Sea [*Perovich et al.*, 2015], an Arctic location that experienced a dramatic loss of sea ice coverage at the end of summer 2007 despite

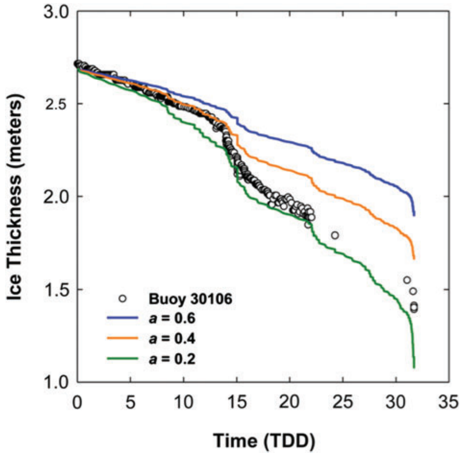

Figure 6. Summer ice thickness as a function TDDs (see text for definition). The black circles represent ice thickness and temperature data returned from Buoy 30106 in the Beaufort Sea. TDD = 0 corresponds to 4 June, and TDD = 32 corresponds to 25 August, after which the buoy ceased to return data. The colored curves represent our model predictions, assuming different values of the late-summer albedo. An albedo of 0.3 closely matches the data. The fact that ice thickness decreases in late summer without an increase in TDDs signifies that melting is predominantly attributable to insolation.

being covered with ice in most previous summers. Because the IMB buoys are designed to function in thick, perennial ice sheets, data was only collected through 25 August 2007, data collection ceasing shortly after the part of the ice sheet that the IMB buoy was mounted to melted to less than 1.5-m thick. This particular buoy is also useful because of its limited coverage area. The buoy drifted only in an area spanning a longitudinal range of 73.1°N–77.4°N and a latitudinal range of 146.6°W–159°W, with coverage area of only 1.68×10^5 km^2, smaller than the coverage area of other buoys.

In Figure 6 we show the results of our model calculation using the temperatures at the location of buoy 30106, benchmarked against the ice thickness it recorded. We display ice thickness as a function of TDDs. The first day above freezing (TDD = 0) was 4 June, and 32 TDDs had elapsed by 25 August, after which the buoy stopped recording data. In the last summer, ice melted by insolation even though the temperatures were essentially at or below the freezing point. Around 29 June, at 15 TDDs, melt pools became prominent enough to lower the albedo, although it is difficult to constrain the melt pool fraction. We start our calculations presuming initial thickness of 2.7 m, and assume three different late-summer albedos: $a = 0.6$ (blue curve), $a = 0.4$ (purple curve) and $a = 0.2$ (red curve). The observed ice thickness (green crosses) are well matched by a model in which $a = 0.30$. For this value of the albedo, the late-summer melting rate matches the observed rate of 4.6 cm per TDD. These calculations highlight the importance of insolation as the driver of melting: the melting rate due to heat transfer alone would be $(h/\rho_i\, l_i) = 0.77$ cm per TDD, and after 35 TDDs, the ice would only decrease in thickness by 0.27 m. Thus, our results are most sensitive to assumptions about albedo, and relatively insensitive to assumptions about temperature and wind speed.

The fact that insolation dominates, and melting is insensitive to the details of the air temperature, suggests that we can treat the two effects separately. We assume that the albedo changes abruptly on 30 June, from 0.75 to 0.30. We find that insolation alone is responsible for 1.11 m of melting over the entire summer at 90° latitude. The amount melted increases with more southerly latitudes, climbing to 1.22 m at 75°N, and 1.38 m at 65°N. The melting of sea ice is mostly due to insolation, which is more-or-less independent of the air temperatures, as well as heating by the air. We predict that at 75°N, by the end of the summer, the combined effects of insolation and 32 TDDs would lead to 1.47 m of melting: 1.22 m from the insolation, and 0.25 m from the heating by air. In this sense, insolation at 75°N is equivalent to 158 TDDs (or 144–179 TDDs at other latitudes). The sea ice at 75°N in the Beaufort Sea does not melt completely, only because that region experiences net negative thawing degree days, with TDD = −200 (Figure 3).

2.4. Effect of Thicker Ice in the Arctic Summer

With a model in hand to calculate the thickness of ice over the course of an Arctic winter and summer, we can estimate how well adding 1 m of ice to the Arctic can counteract existing trends. It is noteworthy that half of the Arctic sea ice currently has a mean annual thickness of only 1.5 m (Figure 3). Adding 1 m of ice in the course of one winter is a significant change. Also evident from Figure 3 is the fact that the mean annual thickness of ice decreased by 0.58 m per decade over the years 2000–2012 [*Lindsay and Schweiger*, 2015]. Adding 1 m of ice to the average thickness of the Arctic is equivalent to instantaneously setting back the clock about 17 years. Implementation over the entire Arctic in the early 2030s, in 1 year adding 1 m of ice, would reset the clock to the present day, instead of the largely ice-free summer state one expects by the 2030s.

But in fact, the effects are likely to be cumulative. Artificial pumping could add an additional 1 m of ice *every* winter. In this sense, implementing artificial pumping in 10% of the Arctic Ocean could have the effect of offsetting 1 m per decade decline in mean annual sea-ice thickness, more than enough to counteract current trends.

Another way to judge the efficacy of increasing ice thickness is to assess how much longer ice extent would survive in the summer. Currently, we expect ice of thickness 2.7 m to survive the summer at the location of the Beaufort Sea buoy, melting only 1.5 m; but if the ice started the summer thinner than 1.5 m, it would melt before the end of the summer. Using our melting model described above, we calculate that sea ice would survive the summer if it started at 1.5 m or thicker, would melt on 15 September if it started at 1.4 m, 18 August if it started at 1.2 m, and 4 August if it started at 1.0 m. From these calculations we estimate that each 0.2 m of ice thickness would delay the melting of the sea ice by approximately 3 weeks, depending on the exact initial thickness. Very similar results obtain at different latitudes. As seen in Figure 1, survival of the ice through the Arctic summer is marginal in over half of the Arctic Ocean; in those regions, artificial pumping over the Arctic winter to increase ice thickness by 1 m translates into several months of extra ice extent, potentially enough to last the summer.

We note that if the ice were to survive the entire summer, instead of there being no ice over the entire summer, the albedo difference (0.3 versus 0.06) would be sufficient to reflect back 2.3×10^8 J m^{-2} of sunlight over the course of the summer. Assuming the loss of albedo takes place over the entire 10^7 km^2 of the Arctic Ocean, this would represent a direct global, yearly averaged radiative forcing of 0.14 W m^{-2}, which by itself is a significant portion of the global anthropogenic radiative forcing, approximately 1 W m^{-2}.

Alternatively, we can consider the effect of increased air temperatures. We assume that insolation would not be quite sufficient to melt the ice, but that the extra heating from the warmer air would cause the ice to melt. In that case, addition of 1 m of ice therefore counteracts a melting rate of 0.77 cm per TDD, extending the duration of the ice by about 130 TDDs. Given that locations in the Arctic Ocean typically experience 0 to −200 TDDs (Figure 7), an extra 130 TDDs to melt the sea ice is significant. Since ice melts over the 4 months of June–September, 130 TDDs is equivalent to an increase of about 1.0°C. It is noteworthy that temperatures in the Arctic in summer 2007, which had exceptionally low sea ice extent, were about 0.5°C warmer than the 1971–2000 average [*Kumar et al.*, 2010]. Artificially enhancing the thickness of Arctic sea ice can significantly offset the melting of ice by warmer air temperatures.

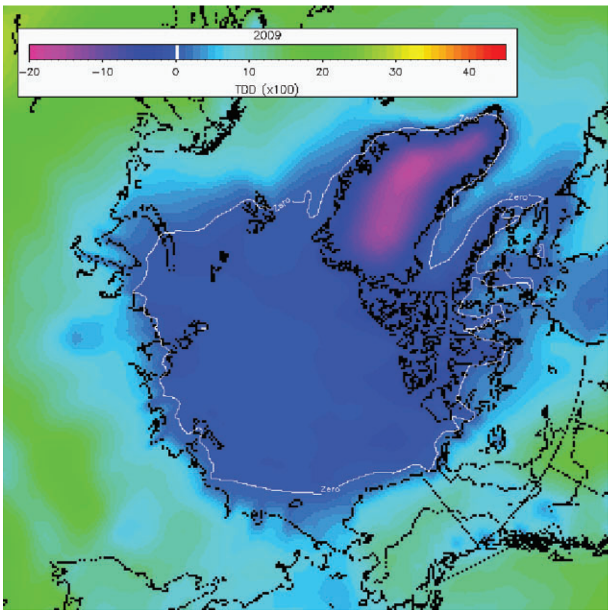

Figure 7. TDDs experienced by different parts of the Arctic in summer 2009, computed using daily mean temperatures from the National Centers for Environmental Prediction dataset. The silver contour hugging the coastlines shows where the net TDDs is zero. Most of the Arctic Ocean is seen to experience between 0 and −200 TDDs per summer. Figure courtesy Yanling Yu and James Maslanik. http://psc.apl.washington.edu/nonwp_projects/landfast_ice/freezing.php

Moving forward, analysis is needed to identify where the multiyear ice is decreasing in thickness or where the net TDDs are increasing. Our analysis so far shows that artificial thickening of the ice can counteract a roughly 1°C temperature increase across the Arctic. Or, for ice that is marginally able to survive the summer, artificial thickening of ice keeps the ice frozen throughout the summer when it might otherwise melt. Addition of 1 m of ice each winter throughout 10% of the Arctic Ocean would offset the current decrease in ice thickness observed since 2000. The potential effects are significant, and it is worth examining how they might be implemented.

3. A Wind-Powered Pumping Device

In this section we examine the feasibility of creating machines or devices that could use wind power to pump roughly 1.3 m of water over the course of the Arctic winter, sufficient to thicken the ice around the device by 1 m. Our goal is to demonstrate feasibility and to provide insights into the scale of the devices. A more detailed design, to be undertaken in conjunction with Arctic engineers is deferred to future investigations.

3.1. Energy Requirements

As described in Section 2, increasing the ice thickness by 1.0 m requires pumping about 1.3 m of water, equivalent to about 1.4 m of ice. This water must be pumped using local energy sources, which in the Arctic winter means using wind. Fortunately, wind is plentiful in the Arctic.

Figure 8 shows the average wind speed in the Arctic over the decade 1986–1996 [*Kalnay et al*., 1996]. The average wind speed over the whole Arctic is $V_w = 6.4\ \mathrm{m\ s^{-1}}$. If this wind is intercepted by a turbine with effective area like a windmill with 6 m-diameter blades, the intercepted power will be $\pi(3\ \mathrm{m})^2\ (1/2)\ \rho_a\ V_w^{\ 3}$ = 5.2 kW, sufficient to pump water a height of 7 m at a rate of 7.5 kg $\mathrm{s^{-1}}$, or 27 metric tons per hour, assuming ρ_a = 1.4 kg $\mathrm{m^{-3}}$ (appropriate for the Arctic winter) and an efficiency of 10%. (It must be noted that wind power density scales as wind speed cubed, so using the mean speed 6.4 m $\mathrm{s^{-1}}$ to derive a power density 180 W $\mathrm{m^{-2}}$ potentially underestimates the average power density. We find that the actual time-averaged power densities range from 170 W $\mathrm{m^{-2}}$ near Greenland to 700 W $\mathrm{m^{-2}}$ in the Barents and Beaufort Seas. Over the course of an Arctic winter, this is sufficient to pump enough water to make 1.5 m of ice over an area approximately 0.1 $\mathrm{km^2}$. Steel wind pumps like those used in agricultural settings for a century typically achieve efficiencies approximately 13%. An example is a commercial windmill 12-m tall, with 6 m-diameter blades, rated to pump 9.6 kg $\mathrm{s^{-1}}$ or 35 $\mathrm{m^3\ h^{-1}}$ in winds 4.5–7 m $\mathrm{s^{-1}}$ like those in the Arctic (http://www.ironmanwindmill.com/images/brochure/brochure.pdf, 10 Jul. 2016). Using different wind turbines, efficiencies closer to 30% would seem achievable, which would pump enough water to cover 0.3 $\mathrm{km^2}$. Sufficient wind energy exists to pump the required amounts of water, but would require on the order of 10 windpumps per square kilometer to capture it.

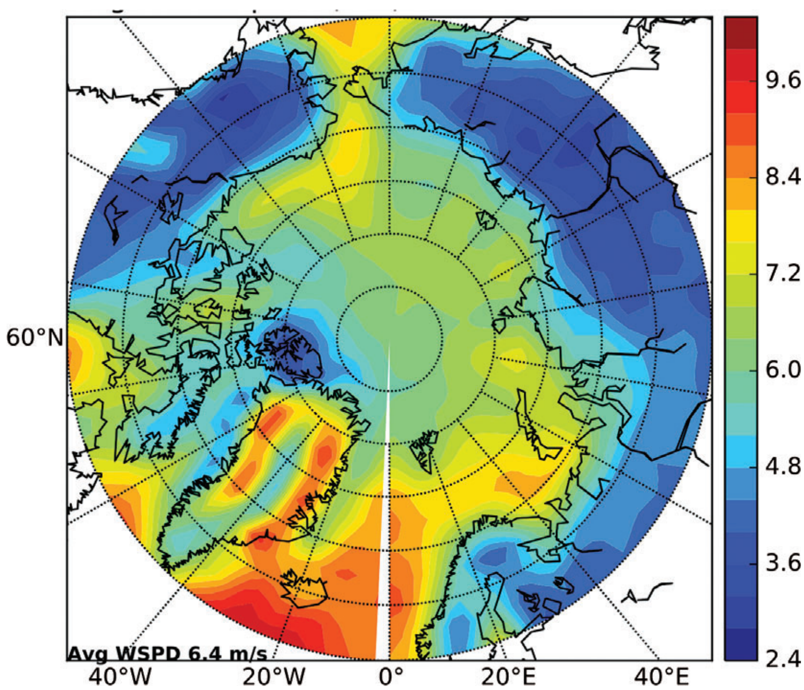

Figure 8. Average wind speed over the Arctic winter, 1986–1996 [*Kalnay et al*., 1996]. Courtesy NCEP/NCAR 40-year reanalysis project. Derived data provided by the NOAA/OAR/ESRL PSD, taken from http://www.esrl.noaa.gov/psd/.

3.2. Description of the Wind-Powered Pump and Its Implementation

We propose that a windpump mounted on a large buoy, could perform the function of capturing wind energy to pump seawater to the surface. While a complete set of design specifications for a wind-powered pumping device and entire AIM system are beyond the scope of this paper, the basic requirements of such a system can be identified. The basic components of such a device would include: a large buoy; a wind turbine and pump, drawing up seawater from below the ice; a tank for storing the water; and a delivery system that takes the water periodically flushed from the tank and distributes it over a large area. The goal is to raise enough water over the Arctic winter to cover an area approximately 0.1 km^2 with approximately 1 m of ice. A system of such devices would have to be manufactured and delivered to the Arctic Ocean, probably repositioned each season, and would need to be maintained.

The engineering challenges of translating even such a common technology to the harsh environment of the Arctic are daunting. Gusts and lulls may increase wind speeds outside the operating range of the turbine, reducing efficiencies. Ambient temperatures are much colder than in other environments; it is a challenge to prevent the water inside the device (tank, delivery system) from freezing. Ice riming (on the outside of the device) is a common and serious problem in the Arctic that a wind turbine design must contend with. The design must also stabilize the buoy so that high winds do not tip over the wind turbine and buoy. Any final design for a buoy-mounted windpump would have to be developed in conjunction with engineers experienced in working in polar environments. That said, we note that many of the needed technologies already have been developed for other purposes. For example, several different wind turbine designs have been used successfully at South Pole station and in the Arctic (https://www.asme.org/engineering-topics/articles/arctic-engineering/wind-turbines-whirling-arctic-regions 5 Oct. 2016), and many of the issues associated with storing and distributing liquid water during the Arctic winter are similar to the problems associated with supplying drinking water in high-arctic communities in the winter, such as the need for heated/insulated storage tanks and distribution systems (http://sciencenordic.com/arctic-town-has-running-water-just-four-months-year, 5 Oct. 2016).

The area of the Arctic Ocean is about 10^7 km^2. If the wind-powered pumps are to be distributed across 10% of that area, this would necessitate about 10 million wind-powered pumps; if distributed across the entire Arctic, about 100 million would be needed. We assume implementation over 10 years, so deploying wind-pumps over the entire Arctic would require 10 million devices per year; deploying wind-pumps over 10% of the Arctic would require 1 million devices per year. Either choice involves a large number of wind-powered pumps to be manufactured, deployed, and maintained, and it is reasonable to ask whether such an endeavor is financially feasible or even logistically possible. To give a perspective on the scale of the enterprise, we estimate the total amount of steel needed, the total shipping capacity required to deliver them, and the total cost.

If each wind-powered pump moves roughly 10 kg s^{-1} of water, it would require a wind turbine with blades on order 6 m in diameter, with weight on the order of 4000 kg of steel. To keep this afloat would require the buoy contain a roughly equal weight of steel. As a round number, we estimate about 10,000 kg of steel would be required per device. To build a fleet of 10 million wind-powered-pumps to deploy over the Arctic over the course of 10 years would require use of roughly 10 million tons of steel per year, or 100 million tons of steel per year to deploy over the entire Arctic. For comparison, the U.S. currently produces about 80 million tons of steel annually, and world production of steel is 1600 million tons per year, half of it in China (http://www.worldsteel.org/dms/internetDocumentList/statistics-archive/production-archive/steel-archive/steel-monthly/Steel-monthly-2015/document/Steel%20monthly%202015.pdf 10 Jul. 2016). We estimate that deployment of devices over the entire Arctic in one year would consume essentially all of U.S. steel production, but only 6% of world production. Deployment over 10% of the Arctic would use 13% of current U.S. production, and $<$ 1% of world steel production.

We estimate that the volume of each device would have volume on the order of 150 m^3, or roughly four 20-foot-equivalent units (TEUs) in shipping parlance. To deliver 10 million devices per year would require a shipping capacity of 40 million TEUs. Assuming each ship could make six trips to the Arctic per summer, a fleet of ships with 7 million TEUs would be required, or 0.7 million TEUs to deploy over 10% of the Arctic. The total worldwide container ship capacity today is approximately is 15 million TEUs, of which 10% is idle at any time (http://www.statista.com/statistics/263970/capacity-of-the-container-ship-fleets-of-the-largest-shipping-companies/ 10 Jul. 2016). Thus, deployment of the devices over the entire Arctic in 10 years would require about half of the current worldwide container ship capacity, but deployment over 10% of the Arctic would not even use all the idle shipping capacity.

Logistically, production and deployment of millions of wind-powered pumps is possible, but at what cost? The cost of 10,000 kg of steel, assuming current costs of $1.30 per kg, would be on the order of $13,000. The manufacture of the devices would not be more complicated than the manufacture of an automobile, and we estimate the manufacturing costs to be a few tens of thousands of dollars. A typical shipping rate for a 40-ft container is about $800 for an 8000-km distance (https://cargofromchina.com/sea-freight/, 10 Jul. 2016). The round trip from, say, Long Beach to the Arctic and back would be about double this. As a round number, we estimate a shipping cost of $4000. Altogether, we estimate a cost of manufacture and deployment per device on the order of $50,000. To deploy such devices over the entire Arctic in 10 years would require about $5 trillion, or about $500 billion per year. To deploy the devices over 10% of the Arctic in 10 years would require about $50 billion per year. We assume that the costs of maintenance would be smaller than the manufacturing costs, aided in part by recycling of corroded steel tanks instead of relying on new steel production.

It is important to put in perspective these costs—either $500 billion per year for the entire Arctic, or $50 billion per year for 10% of the Arctic. Even $500 billion per year represents only 0.64% of current world gross domestic product (GDP) of $78 trillion, 2.7% of the current U.S. GDP of $18.5 trillion, or 13% of the current U.S. federal budget of $3.8 trillion. For comparison, every year the global automotive industry produces 90 million automobiles, and the U.S. automotive industry produces about 10 million vehicles and over $300 billion of revenue (http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_23.html_mfd, 10 Jul. 2016). Thus, deploying devices over the entire Arctic is an enterprise comparable in scope to the U.S. automotive industry, or the execution of the Iraq War, which is to say that it is expensive but is economically achievable. There is a reasonable expectation that this money, largely spent on manufacturing, would stimulate the economy and encourage economic growth. While clearly expensive, constructing and deploying the pumping devices over the entire Arctic is economically achievable. It is also clear that deployment of devices over 10% of the Arctic, at $50 billion per year, is actually economically quite tractable.

A final, reasonable question is whether the environmental costs would outweigh the benefits. Every ton of steel produced would create 1.8 tons of CO_2, so production of 10 million devices per year with 10 tons of steel each would generate on order 0.18 Gt of CO_2 annually. Compared to the worldwide annual production of 36 Gt, this is a negligible increase of 0.5% in annual CO_2 production. Assuming that the CO_2 emissions associated with the other industrial processes needed to manufacture and deploy the devices scale with the economic cost, these are also negligible. The efforts described here, representing no more than 0.6% of the gross world product, probably represent a similar fraction of the worldwide CO_2 production.

We have presented the costs if 100% or 10% of the Arctic Ocean area were to be covered by these devices. In fact, the production of ice by these devices is so efficient that they may counteract the changes in the Arctic if they were deployed only over just 10% of the Arctic Ocean (see Section 4 below). In that scenario, deployment over 10 years would cost about $50 billion per year; construction of the devices would require only 13% of the U.S. steel production; and deployment of the devices would require only 5% of the worldwide shipping capacity. Other aspects appear even more economically feasible.

4. Discussion

4.1. Summary

In this manuscript, we have outlined the importance of the Arctic in the Earth's climate system. The rapid and alarming loss of Arctic summer sea ice represents a powerful and detrimental positive feedback in the system that must be arrested to prevent even greater changes to the climate. At the current rate of change, the Arctic will be completely devoid of late-summer ice by the 2030s, if not sooner. Given the unlikelihood that the global climate changes that are triggering the loss of ice will be solved by then, we are motivated to investigate means of directly and intentionally increasing the ice thickness.

We have considered the feasibility of using wind power to pump seawater from below the ice to the surface, where it can freeze more easily. We have shown that there is enough wind power in the Arctic that a single windmill with 6 m-diameter blades can pump 1.3 m of water (equivalent to 1.4 m of ice) over about 0.1 km^2 over the Arctic winter. By developing a simple model of freezing of Arctic ice in the winter, and melting of ice by sunlight and warm air in the summer, we have demonstrated that pumping this amount of water will increase the thickness of the ice by about 1.0 m over the course of an Arctic winter. Given that the mean annual thickness of Arctic ice is close to 1.5 m, this represents a significant (~70% increase) thickening of the ice.

We have estimated the degree to which this additional ice can counteract changes in the climate. The mean annual thickness of ice is decreasing by 0.58 m per decade, so adding 1 m of ice in 1 year would increase the ice thickness at a rate approximately 17 times greater. It is equivalent to adding 10^4 km^3 of ice per year, approximately 30 times greater than the rate at which ice volume is decreasing, 3200 km^3 per decade. It therefore seems feasible to counteract the changes in the Arctic by deploying the devices over only 10% of the area of the Arctic Ocean. There is less advantage in adding ice off the Canadian archipelago and Greenland, since in these regions perennial ice routinely survives multiple summers. It would be most advantageous to deploy the devices where survival of sea ice through the Arctic summer is marginal, especially the Beaufort Sea, the Chukchi Sea, Laptev Sea, and especially the East Siberian Sea. In regions where summer sea-ice survival is marginal, we estimate that ice thickened by 1 m can survive additional months through the summer, significantly reducing the amount of sunlight that is absorbed over the summer and restoring the ice-albedo feedback to its previous state.

We have presented a concept of a buoy-mounted windpump system that could carry out the required pumping specified above. We have estimated the cost to construct and deploy each device to be comparable to $50,000. To deploy one device per 0.1 km^2 over the entire Arctic Ocean would cost on the order of $5 trillion, but if devices are deployed over only 10% of the Arctic Ocean, over 10 years, the costs are only $50 billion per year. The largest obstacles include producing the required steel and delivering the devices to the Arctic. Deployment over only 10% of the Arctic, though, would require consumption of only about 13% of the U.S. steel production, and roughly 5% of worldwide container ship capacity. These are expensive propositions, but within the means of governments to carry out on a scale comparable to the Manhattan Project.

4.2. Open Questions about the Technique

We have outlined a means for artificially thickening Arctic sea ice. Application in 10% of the Arctic area, particularly the Beaufort, Chukchi, Laptev, and East Siberian Seas, potentially could increase the mean annual thickness of the sea ice Arctic-wide by about 1 m per decade, and increase ice volume by 10^4 km^3 per decade, sufficient to counteract the overall loss of ice in the Arctic. Thus our approach is plausible in broad brush, but there are several details about the technical approach we do not address here.

There are questions about the feasibility: does the proposed technique actually lead to local thickening of the ice over a year? Would the proposed device actually work robustly over multiple seasons, or are conditions in the Arctic too harsh? Could a system be designed to passively deliver water over a 0.1 km^2 area, or is some means of active control necessary? Can the common problems machinery faces in Arctic conditions be solved? Also, because this technique generates ice by putting seawater at the surface, the ice would contain more salt than if the seawater froze to the bottom of the sea ice. The difference is probably slight, as first-year sea ice is naturally salty, becoming fresher each year by the process of brine rejection. But it is not clear how this would affect summer melting or the strength of the ice. Questions about the feasibility of the device and its local effects are probably best solved by building a prototype and experimenting with it in the field.

There are also questions about the feasibility of scaling the device from a local scale to a regional scale. It is desired that the extra ice created by the devices be transported by winds and currents from their region of deployment (e.g., Beaufort, Chukchi, Laptev and East Siberian Seas) to add extra ice over the entire Arctic. In general, currents in the Arctic accomplish just that [e.g., *Polyak et al*., 2010]. It is essential, though, that the buoys *not* be transported away from these regions of marginal ice production, and that they remain in the regions where they would have maximum impact. An economical plan must be developed for periodically (every few seasons) extracting the buoys from the ice during the summer and relocating them. (We note, though, that if the buoys remain unextractable, encased in ice, they will have largely accomplished their mission.)

Then there are questions about the impact a general deployment of the devices would have on the Arctic climate. It is certainly necessary to exhaustively quantify the impact on global temperature, winds, and precipitation patterns this approach would have, using Global Climate Model (GCM) simulations. We note one example of such work by *Sewall and Sloan* [2004], who find that disappearing sea ice causes a drying of western North America. Likewise, connections may exist between Arctic ice extent, release of latent heat near the surface, and the frequency of mid-latitude storms [*Overland et al*., 2015]. The risks or benefits of restoring or increasing Arctic sea ice will be far-ranging. Along the same lines, since we predict that deployment of these devices over just 10% of the Arctic to be capable of generating more ice per year than is currently being lost due to climate change, the possibility exists that the Arctic sea ice would not only increase over time, but could actually exceed the extent seen in previous decades. Could this approach be used to help the Arctic cool the Earth more effectively than it did in the 1980s and before? The effects of *adding* sea ice to the Arctic are completely unknown and also must be judged using GCM simulations.

As is apparent, AIM is effectively a SRM mechanism, and the same questions raised about those techniques should be raised here. If the mechanism is found to create unanticipated negative effects, how quickly could it be halted? These devices could be turned off and cease to produce extra ice at any time. If they did manage to thicken the ice by 1-m Arctic-wide, and then it was decided that this was an unwanted effect, the disappearance of the Arctic sea ice would continue apace at 0.58 m per decade or more, and an extra 1 m of ice across 10% of the Arctic would vanish in a few years. Here again, GCM models should be used to assess the validity of this claim. But we do point out the contrast to the commonly discussed SRM strategy of introducing sulfate aerosols, which will persist in the stratosphere for several years, and which will certainly alter the chemistry in the Arctic. We view as an advantage of the AIM approach that it is merely amplifying an ongoing natural process, with the goal of restoring the sea ice extent to its historical levels.

There are also questions about the collateral effects of producing and deploying such a large number (at least 10 million) buoys across the Arctic. We have argued that the impact on CO_2 emissions is probably negligible, but the environmental impact of the manufacture of so many devices, comparable in scope to the automotive industry, should be assessed. The effects of the presence of the devices themselves on local Arctic ecosystems, and their interaction with sea life, should be assessed as well.

We stress that even if the technical problems associated with AIM were solved, and the ice in the Arctic were to thicken as we (tentatively) predict, this would not "solve" all the problems of anthropogenic climate change. Many severe problems would persist, notably the acidification of the ocean; ocean pH is decreasing by 0.0019 units per year due to increased CO_2 in the atmosphere [*Doney et al*., 2009]. We consider AIM to be a potential means of arresting or possibly reversing the loss of ice in the Arctic, thereby interrupting the ice-albedo feedback. We predict some reduction in direct radiative forcing that may serve to cool the Earth, but the primary advantage of AIM is to prevent the loss of sea ice and the increase in sunlight absorption that would accompany it. Other problems like ocean acidification would have to be solved by other means (e.g., reduction in CO_2 emission and/or carbon dioxide capture and sequestration). AIM is just one potential component in a multipronged strategy for dealing with all the problems of climate change.

4.3. Possible Expansions of AIM

AIM using increased ice production seems feasible, but may benefit by simultaneous use of SRM techniques. In previous decades, winter freezing seems to have generated ice faster than summer melting has destroyed it. As climate change has led to warmer temperatures that balance has shifted to greater melting. We have outlined a means for creating more ice during the winter, but equally effective might be finding a way of slowing the melting of ice during the summer. According to the melting model we present, melting is mostly caused by insolation rather than contact with warm air. To be sure, warmer temperatures represent the greatest change in the system, but the best way to prevent melting of Arctic sea ice would be to limit insolation, as suggested by *Caldeira and Wood* [2008]. Instead of using sulfate aerosols to reflect sunlight, though, we suggest that production of low-lying clouds by marine cloud brightening [*Committee on Geoengineering Climate*: *Technical Evaluation and Discussion of Impacts*, *Board on Atmospheric Sciences and Climate*, *Ocean Studies Board*, *Division on Earth and Life Studies*, *National Research Council*, 2015a, 2015b]. Marine cloud brightening has already been suggested as a tool for slowing Arctic ice loss [*Jones et al*., 2009, 2010; *Rasch et al*., 2009; *Latham et al*., 2014]. We encourage further studies of this technique, especially in conjunction with ice production.

Besides preventing the loss of Arctic sea ice, there may be auxiliary benefits of producing sea ice. For example, a pilot study on a smaller scale in the Canadian Archipelago could be used to extend polar bear as well as marine mammal habitat (W. Broecker, personal communication, 2013). A pilot demonstration in a coastal region would be simpler to execute than the mooring- or buoy-based design we describe here and would still mitigate critical environmental changes that affect charismatic megafauna in the Arctic. Such a pilot project would likely garner significant support from the public because it involves large endangered mammals. Given that it seems possible to produce a surplus of ice, it may be worth revisiting the older, provocative idea of harvesting icebergs to supply drinking water to areas of the U.S. or elsewhere that face intense drought. Early assessment of the icebergs for drinking water idea was premised on the idea of harvesting ice in Antarctica and towing it to southern California [*Hult and Ostrander*, 1973], an idea further explored by *Wadhams* [1990]. This idea appears feasible, although a major consideration is melting losses during transit. If this proposed AIM project could generate excess ice, this ice could be used to augment drinking water supplies. The transport distances to southern California are significantly shorter from the Arctic than the Antarctic and, importantly, do not involve long distances across warm, equatorial regions.

Finally, we suggest that ice production in the Antarctic be considered and assessed as well, although sea ice extent has not suffered as greatly in the Antarctic as in the Arctic, if at all, in large part because ice production in the Antarctic is almost entirely seasonal, with little reliance on multiyear ice production [*Polyak et al*., 2010]. Intervention in the Antarctic may be prohibited by the Antarctic Treaty; nevertheless, the effects of additional ice on the global climate ought to be considered, as well as the effects on glacial flows of emplacing extra ice at their outlets.

4.4. Stakeholders

It is clear that a discussion of AIM quickly moves from technical questions to broader ones involving politics, economics, and society. For AIM to be more than a geoengineering conceit, a large fraction of the potential stakeholders should be identified and engaged in conversation at the outset. The list of stakeholders is, of course, large and includes political, cultural, economic, and social organizations at a minimum. In an ideal world, a multinational governance of the Arctic ice is needed; in the near term, such structures do not exist. We feel that this conversation must include the cognizant governments of countries with territorial claims to the Arctic Ocean (e.g., Canada, Denmark, Norway, Russia, U.S.) as well as international forums, non-governmental agencies (NGOs), and the public. International cooperation is absolutely necessary, given that the effects of the devices would be maximized by deploying them in regions like the Laptev and East Siberian Seas, which are within Russia's Exclusive Economic Zone.

The Arctic Council is an intergovernmental forum tasked with the promoting cooperation, coordination, and interaction among the Arctic States, Arctic indigenous communities and other Arctic inhabitants on common Arctic issues, particularly issues of sustainable development and environmental protection in the Arctic. Many Arctic Council working groups are related to protection of the Arctic ecosystems and the Arctic marine environment. Notably, the Arctic Council has agreed to "*periodically review the status and adequacy of international/regional agreements and standards that have application in the Arctic marine environment*, *new scientific knowledge of emerging substances of concern*, *and analyze the applicability of a regional seas agreement to the Arctic*." (http://pame.is/index.php/projects/the-arctic-ocean-review-aor). The recent Arctic Ocean Review (AOR) Project [*PAME*, 2013] calls out the loss of Arctic sea ice as a critical concern. However, we note, there is no mention in the AOR of mitigating loss of sea ice through deliberate ice formation. This suggests that geodesign is not yet considered a serious mitigation strategy for the Arctic. More generally, the range of NGO's that are concerned with climate change, biodiversity, and environmental degradation is large (e.g., World Wildlife Fund, The Nature Conservancy, etc) and should be engaged at a high level before geodesign projects are conceived and initiated.

Another critical challenge to AIM or any of these geodesign ideas is the issue of social or cultural buy-in. The public often falls into two camps with respect to climate change: denial or despair. Dispensing for now with the problem of denial (the scientific evidence for sea ice loss is incontrovertible), we consider despair to fundamentally stem from the perceived scale and intractability of the problem. The scale of this human-caused problem is certainly immense, but then again so is the scale of human activity. Alteration of the climate has been an *accidental* byproduct of a tremendous amount of human industrial activity. That activity in 2014 put 32 billion tons of CO_2 into the atmosphere, an amazingly large number that is hard for anyone to truly intuit, whether they are in the lay public or in the scientific community. Also difficult to intuit is the scope of what that same industrial activity in one year has created: the production of 1.7 billion tons of steel, the building of 6 million gross tons of shipping capacity, and the construction of over 90 million automobiles. The Gross World Product in 2014 was an astronomical \$78 trillion dollars. Only a small (~0.7%) fraction of that output need be redirected to make an *intentional* difference in the climate. On this basis, the problem is tractable, even though the scale of the problem and the scale of the needed response are both hard to fathom. But for intentional climate intervention to take place, it is politically and ethically necessary for the public to provide their consent.

A recent report from the Royal Society of the U.K. found that geoengineering is a necessary path forward, but cautioned that coordinated and collaborative international efforts are needed and that stakeholder involvement and public dialog are critical frameworks [*Royal Society*, 2009]. The idea of geodesign is complementary and fully analogous to the "Oxford principle" that geoengineering is a public good [*Rayner et al*., 2013] and, furthermore, that appropriate levels of governance, public participation, independent assessment, and open publication are key elements of the process. It will take significant and sustained effort toward education and public outreach to convince the public and decision makers that something can be done, and to seriously consider various geodesign ideas. This work, proposing AIM as a means of intentionally preventing severe feedbacks in the climate system, is a first step in communicating these ideas. It is our hope that this manuscript provokes continued discussion in the scientific community of the technical merits of AIM, in parallel with a public discussion of the morality and ethics and politics of the approach. While humanity does not lack resources, or the imagination and industry to use them, what we do not have in abundance is time.

Appendix A. Freezing of ice over the Arctic winter

Here we present a model for freezing of ice over the Arctic winter that allows us to calculate the ice thickness x as a function of time, t. We benchmark this against an empirical model. Our goal is simply to present a reasonable model for $x(t)$, so that we can assess the additional ice thickness after pumping water to the surface.

In order for ice to freeze, the latent heat of fusion must be carried through the ice shell to the surface, where it can ultimately be radiated to space. The heat flux through the ice is $F = k(x)\,\mathrm{d}T/\mathrm{d}x$, where $x(t)$ is the thickness of the ice shell at some time t and $k(x)$ is the thermal conductivity of the ice at a depth x. Following *Trodahl et al*. [2001], we set $k(x) = k_\mathrm{i} = 2\ \mathrm{W\ m^{-1}\ K^{-1}}$ for $x < x_0 = 0.5$ m, and $k(x) = 0.5\ k_i\ [\ 1 + x/x_0\ ]$ for $x \geq x_0$. We also assume a thin layer of snow on the surface with thickness d_s and thermal conductivity k_s.

The temperature difference, ΔT, between the base of the ice shell, at $T = -1.8°$C, and the surface, at a much colder temperature, is assumed known, and the heat flux, F, through the ice shell is uniform, so it is possible to relate the flux to the thickness of the ice, integrating $\mathrm{d}T = (F/k)\,\mathrm{d}x$. If $x < x_0$, we find

$$\int_{-d}^{x} \mathrm{d}T = F\int_{-d}^{0}\frac{\mathrm{d}x}{k_s} + F\int_{0}^{x}\frac{2\,\mathrm{d}x}{k_i\left(1+\frac{x}{x0}\right)}$$

so that

$$\Delta T = \frac{F\,x_0}{k_i}\left\{c + 2\ \ln\left(1+\frac{x}{x_0}\right)\right\}$$

$$F = \frac{k_i\,\Delta T}{x0}\left\{c + 2\ \ln\left(1+\frac{x}{x0}\right)\right\}^{-1}$$

where $c = (k_i\,/k_s)\,(d/x_0)$. In the absence of snow, $c = 0$.

If $x \geq x_0$, then

$$\int_{-d}^{x} \mathrm{d}T = F\int_{-d}^{0}\frac{\mathrm{d}x}{ks} + F\int_{0}^{x0}\frac{2\,\mathrm{d}x}{ki\left(1+\frac{x}{x0}\right)} + F\int_{x0}^{x}\frac{\mathrm{d}x}{ki}$$

and

$$\Delta T = \frac{F\,x0}{ki}\left\{c + 2\ \ln 2 + \left(\frac{x}{x0} - 1\right)\right\}$$

and

$$F = \frac{ki\ \Delta T}{x0} \left\{ c + 2\ \ln 2 - 1 + \frac{x}{x0} \right\}^{-1}$$

We next equate the growth of ice with the rate at which the latent heat of fusion can be conducted away,

$$F = \rho_i l_i \frac{dx}{dt}$$

Integrating $dt = \rho_i\, l_i\, dx/F(x)$, we find:

$$\frac{FDD}{442.4} = c + 2\left[\left(1 + \frac{x}{x0}\right)\ \ln\left(1 + \frac{x}{x0}\right) - \left(\frac{x}{x0}\right)\right],$$

where we have assumed $k_i = 2\ \mathrm{W\ m^{-1}\ K^{-1}}$, $\rho_i = 918\ \mathrm{kg\ m^{-3}}$, and $l_i = 3.34 \times 10^5\ \mathrm{J\ kg^{-1}}$, and we have written the left-hand side in terms of "Freezing Degree Days" $FDD = (\Delta T/1\ \mathrm{K})\ (t/86{,}400\ \mathrm{s})$. The above expression relates $x(t)$ to FDD until $\mathrm{FDD} > \mathrm{FDD}_0 = 442.4\ (c + 4\ln 2 - 2)$, after which

$$\frac{\mathrm{FDD}}{442.4} - \frac{\mathrm{FDD}_0}{442.4} = \int_{x0}^{x} \left[c + 2\ln 2 - 1 + \frac{x}{x0}\right]\ dx,$$

or

$$\frac{\mathrm{FDD}}{442.4} = (c + 4\ln 2 - 2) + (c + 2\ \ln 2 - 1)\ \left(\frac{x}{x_0} - 1\right) + \frac{1}{2}\left(\frac{x^2}{x_0^2} - 1\right).$$

This admits a closed-form solution for x for $\mathrm{FDD} > \mathrm{FDD}_0$:

$$x\,(\mathrm{FDD}) = -x0\ \left[c + 2\ \ln 2 - 1\right] + x0\ \left[2\frac{\mathrm{FDD}}{442.4} + 3 - 4\ln 2 + (c + 2\ln 2 - 1)^2\right]^{\frac{1}{2}}.$$

The parameter c is uncertain, but we now choose it to minimize the differences between this equation and the empirical fit by *Maykut* [1986]:

$$x_M\,(\mathrm{FDD}) = 0.0133\ \ (\mathrm{FDD})^{0.58}\ \ m$$

Specifically, we minimize the average discrepancy between our formula and the empirical fit by *Maykut* [1986], in the time interval $0 < \mathrm{FDD} < 5000$, if we adopt $c = 0.68$, in which case

$$x\,(\mathrm{FDD}) = -0.5331 + 0.5\left[\frac{\mathrm{FDD}}{221.2} + 1.3644\right]^{1/2}\ m$$

the average discrepancy is $< 5\%$, and the two formulas agree to within 10% for $FDD > 700$. Given a thermal conductivity of snow $k_s = 0.045\ \mathrm{W\ m^{-1}\ K^{-1}}$ [*Pomeroy and Brun*, 2001], $c = 0.68$ implies a thickness $d_s = 8$ mm.

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