Preserving Arctic and Antarctic Ice: Ideas about Artificial Processes

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Abstract

Catastrophic ice loss from the Arctic and Antarctic may lead to large-scale changes in both weather and climate. From a human perspective, the worst case resulting would be changes to weather circulation such that rain patterns would be disrupted significantly. The impact on global agriculture is worth studying. Preliminary thoughts related to modelling this question will be presented as a part of ongoing research. Also, methods and estimates related to artificially thickening ice at the poles perhaps to prevent such a loss will also be presented in a preliminary form.

Keywords:

Climate Change, Geoengineering, Polar Research, Sea Ice, Ice Sheet

Preliminary Thoughts

Ice is melting from the Arctic and Antarctic. Humans are ingenious enough to put people on the moon, genetically engineer crops, create sex reassignment surgery for those who want it, and a host of other things—ranging from trivial to significant. Keeping ice at the Earth's poles artificially would probably be a significant accomplishment. Medals would be minted and celebrations would mark the accomplishment. Humanity could breathe a small sigh of relief as it moves on to tackle some other challenge.

At its simplest, artificially adding ice to the Arctic and Antarctic is a two-stage challenge: (1) get water to the right place; and (2) let it freeze. Perhaps an optimal solution to the first part is to try and use the closest water possible, maybe seawater that is there. The second part is complicated by the means of transport. Water should not freeze before it is where it needs to be. Any technique to promote transport cannot do so at the expense of freezing once it has arrived.

Global Functions of Arctic and Antarctic Ice

The polar ice serves three significant functions related to the climate. First, it increases albedo (Wang & Zender, 2011). Sunlight reflects better from ice than from sea or bare or treed land surfaces. This reflection helps send incident solar radiation back into space. A very cloudy atmosphere does something similar, and it is unclear whether the loss of sea ice at the poles from atmospheric heating will produce a net change in albedo (Goldner et al. 2013). If the ice melts, more water will then reside in the

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atmosphere, and from that there will be greater cloud cover. Notwithstanding, albedo is one significant function of polar ice.

Second, ice sequesters water (Shepherd et al. 2012). Water trapped as the polar ice on land prevents the oceans from rising (Meyssignac & Cazenave, 2012; Raymo & Mitrovica, 2012). Polar ice, along with other glaciers and ice caps, consists of approximately 1.715% of the water in the hydrological cycle (Shiklomanov, 1993). Here is a simple model: If each reservoir in the hydrologic system were to receive an even share of this water—as ice melts and ocean surface area increases—H2O in the atmosphere would increase by about 1–2% of its current level.

H_2O is a greenhouse gas, and increased water vapour in the polar atmosphere could lead to increased greenhouse warming. Because of precipitation, tropospheric water has a short atmospheric residence time (about 10 days), but its presence could amplify the effects of other greenhouse gases by a factor of 2 or 3 (Held & Soden, 2000). Thus, the ice trapped at the poles works to mitigate the effects of other greenhouse gases.

The polar ice has a further likely function of import, a third function. It stabilizes the weather in the polar circulation cell. If there were no ice at the poles, the air near the ocean surface would be warmer than the ice cover is now—as incident sunlight warms it. That warm air would fuel convection, and, in short, there would be increased convection in the troposphere in the polar regions. A model suggests that this is what occurred during the late Cretaceous and early Paleogene, a period of equable climate globally (Abbot & Tziperman, 2008). In this scenario, the shift from one climate regime to another is prevented by the presence of the polar ice. The ice is seen as a stopgap between climate regimes. Preventing the transition from one climate regime to another includes preventing extreme weather events associated with the transition.

If the ice melts wholesale, there is a further issue with convection. The presence of so much freshwater (from the ice melt) would lower the salinity of surface waters, and, hence, their density. Downwelling, which is driven by a density gradient, would slow (Aagaard & Carmack, 1989). The transfer of heat from equatorial oceans to high-latitude oceans is driven in part by the ability of this downwelling to make space for incoming surface waters. If there is less downwelling at high latitudes, heat transfer from equator to high latitudes in the ocean surface waters will be diminished. Extra heat at the equator will fuel stronger storms there. Thus, melting polar ice in volume has the potential to disrupt ocean circulation and make changes to weather.

The converse of the above is also interesting. With thicker polar ice, surface waters are cooled and downwelling increases. Also, since surface waters are enriched in dissolved carbon dioxide from the atmosphere, increased downwelling serves to sequester atmospheric carbon to a certain extent (Zhou & Flynn, 2005). Thicker ice would mean more carbon sequestration. Thus, the polar ice is seen to influence the carbon cycle via its effect on oceanic circulation. The above has highlighted three effects that the polar ice has on convection: (a) limiting atmospheric circulation at the poles; (b) promoting global oceanic circulation to draw heat from the equatorial regions; and (c) promoting carbon sequestration. In summary, this section has highlighted three overall functions of polar ice: (1) increasing albedo; (2) storing water; and (3) stabilizing the climate via convective processes.

Global Agriculture

Climate change implies a disruption of rainfall patterns, which in turn impacts global agriculture. At its most basic, domesticated crops have water requirements that are largely met by rainfall or irrigation based on water discharge (indirectly based on rainfall and snow and ice melt). Fluctuations in rainfall patterns on decadal timescales could reasonably be expected to cause global agricultural disruption. The food supply of humans is thus vulnerable to disruption in the coming decades. Disruption to global climate could have catastrophic consequences for human civilization. Stable city life depends upon stable supplies of agricultural products, as it has for millennia. In response, Wratt et al. (2006) and others are working to provide farmers with up to date information about rainfall, frost, and soil-type patterns, to reduce economic risk in the industry. Uncertainty is significant in crop models, especially related to temperature variations (Lobell & Burke, 2008).

Unfortunately, low-probability, high-impact catastrophes from climate change scenarios are not possible to mitigate effectively (Weitzman, 2009). Could the loss of major ice sheets occur on a decadal timescale? Such a loss may be a point of no return, as the natural re-growth of ice sheets would occur on millennial timescales.

Anatomy of Polar Ice

Sea ice, ice shelf, and ice sheet thicknesses are different from each other, and also different depending on whether they are Arctic or Antarctic. See Table 1. The annual mean Arctic sea ice thicknesses vary from 3.6 m (in 1980) to 2.4 m (in 2000) (Vaughan et al. 2013). The long-term mean Antarctic sea ice thickness is 0.87 m (1981 to 2005; standard deviation 0.91 m) (Worby et al. 2008).

The mean thickness of the Antarctic ice shelves is 440 m (1950 to 2000, 150 surveys, root-mean-square error from about 20 m to about 100 m for different ice shelves) (Lythe & Vaughan, 2001) and that of Antarctic sheet ice is 1856 m, combining both East Antarctic (2146 m) and West Antarctic (1048 m) means, and the distribution has a large peak (or mode) around 2800 m (*Ibid.*). The mean thickness of the Greenland sheet ice is approximately 1600 m (Bamber et al. 2013).

Table 1. Mean Thicknesses of Arctic and Antarctic Sea Ice, Antarctic Ice Shelves, and Antarctic Greenland Sheet Ice

Ice Type	Mean Thickness	Mean Type
Arctic sea ice	2.4–3.6 m	Annual
Antarctic sea ice	0.87 m	Long term
Antarctic shelf ice	440 m	
Antarctic sheet ice	1856 m	
Greenland sheet ice	1600 m	

The extent area of sea ice varies with the seasons, but the Antarctic ice shelves vary more according to patterns in underlying ocean temperature (Vaughan et al. 2013). See Table 2. The Arctic sea ice extent varies from 6.2 to 14 million km2 seasonally, with a volume of 13.0–16.5 thousand km3 (*Ibid.*). The Antarctic sea ice extent varies from 2.9 to 19 million km2 seasonally, with a volume of 3.4–11.1 thousand km3 (*Ibid.*). The Antarctic ice shelf extent is 1.6 million km2, with a volume of 380 thousand km3 (*Ibid.*). The Antarctic sheet ice extent is 8.3% of the global land area, or 12.3 million km2 (*Ibid.*), with a volume of 24.7 million km3, excluding the shelf ice (Lythe & Vaughan, 2001). The Greenland ice sheet extent is 1.2% of the global land area, or 1.8 million km2 (Vaughan et al. 2013), with a volume of 3.0 million km3 (Bamber et al. 2013).

Table 2. Extent and Volume of Arctic and Antarctic Sea Ice, of Antarctic Shelf Ice, and of Antarctic and Greenland Sheet Ice

Ice Type	Area (km^2)	Volume (km^3)
Arctic sea ice	6.2 to 14 million	13.0 to 16.5 thousand
Antarctic sea ice	2.9 to 19 million	3.4 to 11.1 thousand
Antarctic shelf ice	1.6 million	380 thousand
Antarctic sheet ice	12.3 million	24.7 million
Greenland sheet ice	1.8 million	3.0 million

Neither sea ice nor ice shelves melt wholesale. They both calve along zones of weakness, called *leads*, and these leads determine the geometry of the resulting ice loss. The sea ice deforms and fractures in response to stress and strain from (1) wind (a primary force, compressive), (2) ocean currents (a secondary force, mostly compressive), (3) Coriolis forcing (almost negligible), and (4) thermal conditions (important in fracture, tensile), with (1) predominating in deformation and fracturing (Weiss, 2003). Near-surface wind and temperature govern the formation, accretion, movement, and the melting of sea ice (Henderson, Barrett & Lafleur, 2014). In contrast, the calving of ice sheets (and glacial crevasse formation) is mainly a tensile process, related to the velocity of glacier advance or retreat. The main control is in spatially distributed variations in velocity. That is, shelf and sheet ice deformation is controlled by variations in ice velocity (Layberry & Bamber, 2001). Secondary controls are those related to the ice margin itself (e.g., local stress imbalances, melting at or below the waterline or ground, and strain at the junction of grounded and buoyant sections of shelf ice) (Benn, Warren & Mottram, 2007). See Table 3.

Table 3. Predominant Conditions Responsible for Fracture of Sea Ice, Shelf Ice, and Sheet Ice

Ice Type	Condition
Sea Ice	Wind
	Near-Surface Temperature
Shelf Ice/Sheet Ice	Variations in ice velocity
	Stress, strain and melting at the margins

The fracture of both the sea ice and the shelf ice (approximately) follow a cubic scaling law (Weiss, 2003). That is, there are about one-eighth as many ice floes of double a given diameter. The sea ice lead spacing is clustered, with a power law of about 2: There is about one-fourth of the number of spaced leads as the given spacing width is doubled, based on the observation (Weiss, 2003). Glacial crevasses and ice sheet fractures are not clustered; rather, they are evenly distributed, with at least one report of 20–80 m distributions for crevasses (Weiss, 2003).

Artificial Processes

If the polar ice ought to be protected, then technological processes provide one option. A protective process is one that would help to counter the typical fracture of sea ice, the calving of ice shelves, and help to prevent the melting of sheet ice.

One protocol that might be undertaken is the monitoring of shelf and sheet ice for strain. Satellite data showing differential strain in landmasses have been used extensively in earthquake observations (Jet Propulsion Laboratory, 2013). This can be applied to the Antarctic ice shelves (Goldstein et al. 1993). New satellite emplacement may not be required. Strain data may help to plan for the locations of ice weakness and subsequent loss.

In addition to the above, summer melt increases ice porosity (lowering strength) and decreases salinity through flushing, thereby lowering electromagnetic sensitivity: Fresh water is less conductive than saline (Vaughan et al. 2013). Thus, remote electromagnetic sensing may be a mode of gathering data to determine strategic locations for mitigation. In the previous section, it was mentioned that melting on the margins of sheet ice, and notably in the lower margin, is a secondary control on fracture formation. It is conceivable that artificial ice dams might retard the outflow of sheet ice meltwater and thereby retard the melting.

This is the first of three goals that seem relevant: (1) artificial sea ice to prevent meltwater outflow. The other two are (2) new artificial sea ice to prevent loss of sea ice generally; and (3) artificially thickened sea ice. Zhou and Flynn (2005) discuss various options for increasing the downwelling of ocean currents. One of their proposed solutions (and the most cost-effective one examined) is ice sheet thickening. The technique they describe involves a set of unmanned stations that are powered by wind generators. Each has pump and sprayer with high pressure—high enough so that water sprayed to altitude will form small ice crystals. These then fall to the ocean surface, eventually after several cycles forming a layer of ice where none had been before. Each station also has a pump and a sprayer with low pressure, to spray water on already extent ice. The water freezes and the ice is thickened.

They estimate a cost (in year 2000 US Dollars) of $45 billion for the initial set up and an ongoing cost of $1.3 billion annually to install and run 8100 of these stations. That number is what they estimate it would take to create enough ice in the Arctic to increase downwelling by 1 million cubic meters per second as the surface water is cooled, with the goal of sequestering surface water carbon into the deep oceans from this process. See Tables 4 and 5.

A second method of artificially thickening sea ice is suggested in popular media reports for places where ice overlays water. For example, a planned attempt may have occurred at the Tuul River in Ulan Batur, Mongolia (Watts, 2011). Holes were to be drilled in the ice cover of the river during late fall or early winter. Water was to be pumped up through the holes. The water was to be sprayed on top of the ice cover. The idea is the same as with Zhou and Flynn (2005): The water spray freezes, and the ice is thickened, thereby allowing it to withstand melting. It is not clear whether the Mongolian experiment actually took place, and if it did, what the outcome was. Also, this method is likely to be more expensive than what Zhou and Flynn (2005) present, since it involves (1) the additional step of drilling through sea ice, and (2) personnel for the daily running of the operation.

Table 4. Capital Costs for Wind-Powered Polar Sea Ice Generators (adapted from Zhou & Flynn, 2005)

Category	Element	No. of units	Unit cost w/o learning factor ($ k)	Learning factor	Overall cost ($ M)
		Direct Costs			
Barges	Material	8100	1900	0.8	28000
	Labour ($50 hr–1)	8100	1100		
	Overhead and profit	8100	1300		
Wind power	Installed wind power system	8100	450	0.8	3500
	Battery bank	8100	90		
Pumping	Low volume pump	8100	30	0.8	3500
	High volume pump	16200	200		
	Heat tracing and insulation	8100	120		
Transportation	Helicopter	32	1000	1	32
Land-based construction	Control centre and instrumentation	1	70000	1	990
	Harbour and harbour machinery	4	100000		
	Air base	4	130000		
		Indirect Costs			
Engineering and supervision	5% of direct costs	1	1700	1	1700
Contingency	20% of direct costs	1	6900	1	6900
Total					45000

Table 5. Operating and Maintenance Costs (adapted from Zhou & Flynn, 2005)

Category	Element	No. of units	Estimate basis	Unit cost ($ k yr^{-1})	Overall cost ($ M yr^{-1})
Barges	Tug rent	8100	$300 hr^{-1}	20	730
			Deployment and retrieval: 1440 hrs		
			1 tugboat per 20 barges		
	Maintenance	8100	1% of direct costs	40	
	Insurance	8100	1% of total costs (barge, wind power and pumping system)	30	
Wind power	Wind turbine and battery O & M	8100	$0.015 kW–1h–1	15	200
	Battery replacement	8100	10 years lifespan	10	
Pumping	Pump O & M	8100	3% of capital costs	10	240
	Heat tracing O & M	8100	20% of capital costs	20	
Transportation	Helicopter maintenance	32	15% of capital costs	150	26
	Fuel consumption	32	$0.2 litre–1	70	
			230 liters per flight hour		
	Labor and overhead	32		580	
Land-based construction	Control center	1	Building and equipment maintenance: 5% of capital costs	5100	99
			Total personhrs ($75 hr-1): 5400 yr^{-1}		

Category	Element	No. of units	Estimate basis	Unit cost (\$ k yr^{-1})	Overall cost (\$ M yr^{-1})
	Harbor	4	Docks and machinery maintenance: 5% of capital costs	17000	
			Total personhrs (\$75 hr^{-1}): 151200 yr^{-1} per harbor		
	Air base	4	Runway, control tower, and machinery maintenance: 5% of capital costs	6500	
			Total personhrs (\$75 hr^{-1}): 3240 yr^{-1} per base		
Total					1300

Concluding Remarks

This paper has given a brief sketch of a possible area of investment to counter climate change related to the loss of polar ice. The ideas herein are in the public domain. The articles cited are public knowledge. Perhaps a reader will decide that there is some business opportunity here that will have the primary benefit of humanity's greater good. More work needs to be done.

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