Geoengineer polar glaciers to slow sea level rise

Stalling the fastest flows of ice into the oceans would buy us a few centuries to deal with climate change and protect coasts, argue John C. Moore and colleagues.

Greenland and Antarctica's ice sheets will contribute more to sea level rise this century than any other source[1]. A two degree Celsius increase is predicted to swell the global oceans by around 20 cm on average. Most large coastal cities will face sea levels more than a metre higher by 2100[1].

If nothing is done, by the end of the century up to 5% of the world's population will be flooded each year. For example, a 0.5m rise on China's Guangzhou and Pearl River delta would displace over a million people; a 2m rise would affect more than 2 million. Without coastal protection, the global cost of damages may reach US$ 50 trillion a year. Sea walls and flood defences cost tens of billions of dollars a year to construct and maintain[6].

At this price, geoengineering is competitive. For example, Hong Kong's international airport, which involved building an artificial island to add 1% to the city's land area, cost around US$20 billion. China's Three Gorges Dam, spanning the Yangtze River to control floods and generate power, cost $US 33 billion.

We believe that geoengineering glaciers on a similar scale could delay significant amounts of Greenland and Antarctica's grounded ice from reaching the sea for centuries, buying time to address global warming. This is plausible in our view because about 90% of ice flowing from the Greenland[3] and Antarctic[4,5] sheets into the sea travels in narrow, fast streams, tens of kilometres or less across. Fast glaciers slide on a film of water or wet sediment[2]. Stemming the largest flows would allow the ice sheets to thicken, slowing or even reversing their contribution to sea level rise.

Yet geoengineering of glaciers has received hardly any attention in research journals. Most people assume it is unfeasible and environmentally undesirable. We disagree. We understand why most people are hesitant to interfere with glaciers. As glaciologists, we know well the pristine beauty of these places. But we have also stood on ice shelves that are now open-ocean. If we do nothing, ice sheets will keep shrinking and the losses will accelerate. Even if we slash emissions, which looks unlikely, it would take decades for the climate to stabilize.

Is allowing a ‘pristine’ glacier to waste away worth forcing a million people from their homes? 10 million? 100 million? Should we spend vast sums to wall off all the world’s coasts, or can we address the problem at its source? Geoengineering is a political or societal choice. People’s reactions depend on how the issue is framed. Buttressing glaciers needs a serious look. It should have fewer global environmental impacts than other proposals being discussed for reducing sea level rise, such as injecting aerosols into the stratosphere to reflect sunlight and cool the planet.

To stimulate discussion, here we present three ways to delay the loss of the ice sheets.

1. Block warm water Jakobshavn glacier in western Greenland is one of the fastest moving ice masses on Earth. This one glacier contributes more to sea level rise than any other in the northern hemisphere**.** Ice loss from Jakobshavn explains around 4% of 20th century sea level rise, or about 0.06 millimetres per year.

Jakobshavn glacier is retreating at its front. At the mouth of Ilulissat fjord, relatively warm water from the Atlantic is flowing over a shallow sill (300 m deep) and eating away at the glacier’s base (Fig. 1). Making the sill shallower would reduce the volume of warm water and slow the melting. More sea ice would form. Icebergs would lodge on the sill and prop up the glacier.

A 100m-high wall with sloping sides could be built across the 5km fjord in front of Jakobshavn glacier by dredging around 0.1 km^3 of gravel and sand from Greenland’s continental shelf. This berm could be clad in concrete to stop it being eroded. The scale of the berm would be comparable with existing large civil engineering constructions. For example, ten times more material -- 1 km^3 -- was excavated to build the Suez Canal. Hong Kong’s airport required around 0.3 km^3. The Three Gorges Dam used 0.028 km^3 of cast concrete.

Construction would be arduous and potentially hazardous in cold waters littered with ice bergs. Local reactions would be mixed. The project would create employment but large numbers of outside workers would have to be brought in. Ecology, fisheries and tourism may be affected. Glacier sediments supply nutrients for plankton growth and increased turbulence during construction, and loss of sediment once the glacier was slowed, would affect marine ecosystems.

Building such a berm would tell us whether glacial geoengineering is feasible, or of unanticipated consequences. But it would have only a small impact on 2100 global sea levels as Greenland's contribution is likely to be just 10-20 cm. Antarctica will be the largest contributor. And geoengineering there will require even larger and more challenging projects.

2. Support ice shelves

Where Antarctica's ice sheets reach the sea, ice flows out into floating shelves. Pinned by rocks and islands, these platforms hold back glaciers advancing from within the continent and limit how much ice reaches the sea. As air and ocean around Antarctica warm, these ice shelves are becoming thinner. They are breaking up into icebergs, which flow north and melt[8]. In 2002, scientists were shocked when 58% of the vast 9700 km^2 Larsen B ice shelf collapsed. Half a dozen other shelves around the Antarctic Peninsula have shattered in the past 30 years. Those fringing the Amundsen Sea are becoming thinner.

Sheer cliffs are left behind when an ice sheet collapses. These crumble, accelerating the glacier's retreat[10]. The West Antarctic ice sheet is especially vulnerable as its bed rock lies below sea-level and is deeper inland, making it vulnerable to runaway retreat via the marine ice sheet instability[9]. Warm ocean currents in the Amundsen Sea are melting the bottoms of floating parts of the glaciers, making the sheets more unstable **<check ok?].**

The Pine Island[4] and Thwaites[5] glaciers in West Antarctica are the largest potential sources of sea level rise over the next two centuries. Both glaciers are losing height and flowing more quickly: Pine Island Glacier reached about 4km/year in 2009 compared with 2.5 km/year in 1996. Models predict that by 2150 these two glaciers might disgorge ice 10 times faster than present rates, contributing 4 cm per year to global sea level rise (10).

One solution is to artificially pin the ice shelves in front of the two glaciers by constructing berms and islands, extended from outcrops or built on the seafloor**.** For example, the shelf buttressing Pine Island Glacier could be jammed by a berm on Jenkins Ridge, a high point below. We estimate this would require around 6 km^3 of material, 60 times more than for plugging the Jakobshavn fjord. Small 300m-high artificial islands in other places would require 0.1 km^3 of material each. A large berm (10-50 km^3) in the open bay could prevent warmer waters from entering.

Whether such engineering feats would successfully delay sea level rise, and for how long, requires a better understanding of many factors: how the ocean circulates below ice shelves; how floating ice fractures and calves ice bergs; and how glaciers slide and erode at their bases. A thorough study would be needed of the stresses that pinned ice shelves could sustain without fracturing. Models of ice dynamics should determine the most effective locations for pinning.

Material could be shipped to Antarctica from elsewhere in the world, or dredged or quarried locally. But it would be practically difficult for engineers to work around the ice shelves, which grow and shrink as the glaciers, sheets and conditions fluctuate. Sea ice would also get in the way. Technologies may need to be developed to operate beneath floating ice. Major disturbances to local ecosystems would be expected and require thorough assessment.

3. Dry subglacial streams

Fast-sliding ice streams supply 90% of ice entering the sea. Frictional heat as the ice slides over the bed accounts for about 90% of the water at the base of the ice streams. This water acts as a lubricant, speeding up the flow, which in turn generates more heat, and creates more water and slippage.

Glaciers in Greenland and at lower latitudes are relatively wet as their surfaces melt in summer. Summer melt reaches the bed through moulins, building an efficient seasonal drainage system, in contrast to Antarctica, where there is little surface melt reaching the bed.. For example, the base of Pine Island Glacier releases about 50 m^3 of water per second, which is only about 10 mm/year over the catchment (2). Removing this thin layer of water will increase drag, slow the glacier and reduce friction and heating. The glacier will stall and it will thicken.

It is difficult to access the bed of a glacier beneath a kilometre of ice. But there are precedents. The IceCube Neutrino Observatory at the South Pole has used jets of hot water to drill 60 holes to depths of 1500-2500m in the ice sheet. At Engabreen, Norway, 30-40 m^3 of meltwater from the base of a 200 m thick glacier is fed each second to the Svartisen hydropower plant via a 100-km network of 5m-wide tunnels in the underlying rock, which cost around $500 million **<ok? in total].**

Deeper subglacial water in Antarctica is under pressure and should drain to the ocean without pumping. It could also be frozen by circulating cooled brines beneath the 10 m-thick layer of sediment scoured at the glacier’s base. The Pine Island glacier might be reached via the nearby volcanic outcrops of the Hudson Mountains. These lie within 80 km of the glacier and the coast and would be a good base for research into the sub-glacial environment and ice shelves. Again, the costs of such projects appear comparable to other large energy and civil engineering works.

Feasibility trials

Glaciologists and engineers should establish the scientific viability of these projects through fieldwork and computer modelling. The glaciers concerned need extensive study, including mapping the geomorphology of their beds and the rates at which they are melting. More observations are needed of the North Atlantic’s flow onto the Greenland shelf. Climate models need to do a better job of simulating the Southern Ocean.

Potential risks, especially to local ecosystems, need careful analysis. In our view though, the greatest risk is doing nothing – or if the interventions don’t work. The local impacts of construction would be dwarfed by both the local impacts of the ice sheet’s collapse and the global impacts of rapid sea level rise. Unexpected consequences might arise. For instance, if an efficient drainage system exists at the glacier's base, then removing water might accelerate the ice sheet flow. **<ok?]**

Implementation would require global consent. Antarctica is governed by the Antarctic Treaty. Research there is undertaken within the multilateral framework of Scientific Committee on Antarctic Research (SCAR), which meets in June. Countries finance research programmes based on their interests, and a few could take a lead. For example, researchers in China are preparing a $3 billion plan for Antarctic research in the next decade that includes addressing the feasibility of targeted geoengineering schemes like ours. Options for building a research base in the Hudson Mountains, to access the glaciers flowing into the Amundsen Sea, should be discussed.

Around Greenland, sea levels will fall as ice is lost from its interior, reducing the sheets' gravitational pull **<ok?].** This may be as inconvenient for coastal communities as rising seas. Collaborations and cultural exchanges **<meaning what exactly – discussions? Joint research projects?]** might be explored between Greenlanders and those most at risk of rising sea levels, for example in the small island states.

Geoengineering of glaciers will not mitigate global warming from greenhouse gases. The fate of the ice sheets will depend ultimately on how quickly we bring down emissions. If they peak soon, it should be possible to preserve the ice sheets until they are again viable. If emissions keep rising, the aim will become managing the collapse of the ice sheets to smooth the rate of sea level rise and ease adaptation.

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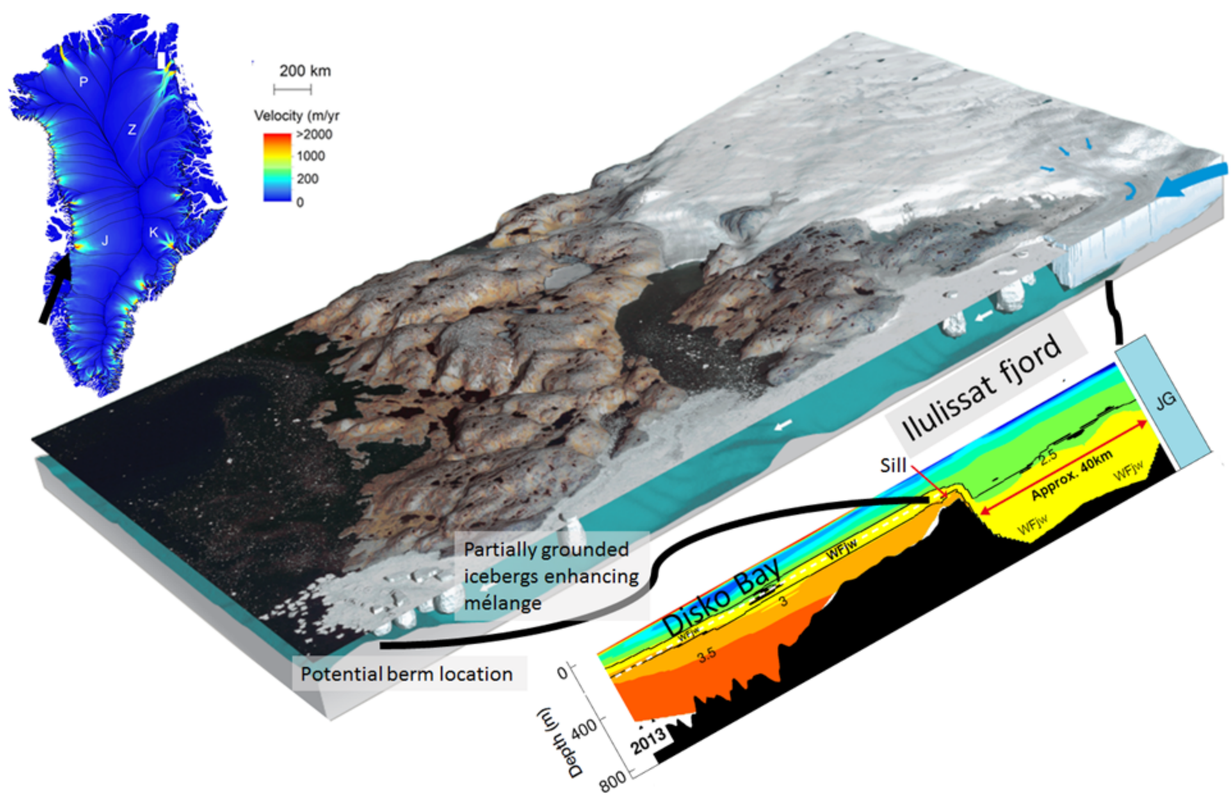

Fig. 1. Jakobshavn Glacier (JG), ice flow (blue arrows) into Ilulisat fjord. The cross section shows observed ocean potential temperatures[7] from summer 2013. Warm Fjord Water (WFjW),in Disko Bay is influenced by the relatively warm and widespread Atlantic Water. A berm on the sill could have two benefits: preventing inflow of warm fjord water and increasing the backstress due to increased grounding of icebergs at the fjord entrance. The inset of Greenland shows the view point (black arrow) for the 3D picture and other large drainage basins with narrow outlets based on a flowline routing algorithm[8] of J: Jakobshavn, Z: Zachariae, and K: Kangerdlugssuaq that have all experienced mass loss recently[3], and P: Petermann glacier. 3D picture courtesy of Carsten Thuesen, Geological Survey of Denmark and Greenland.

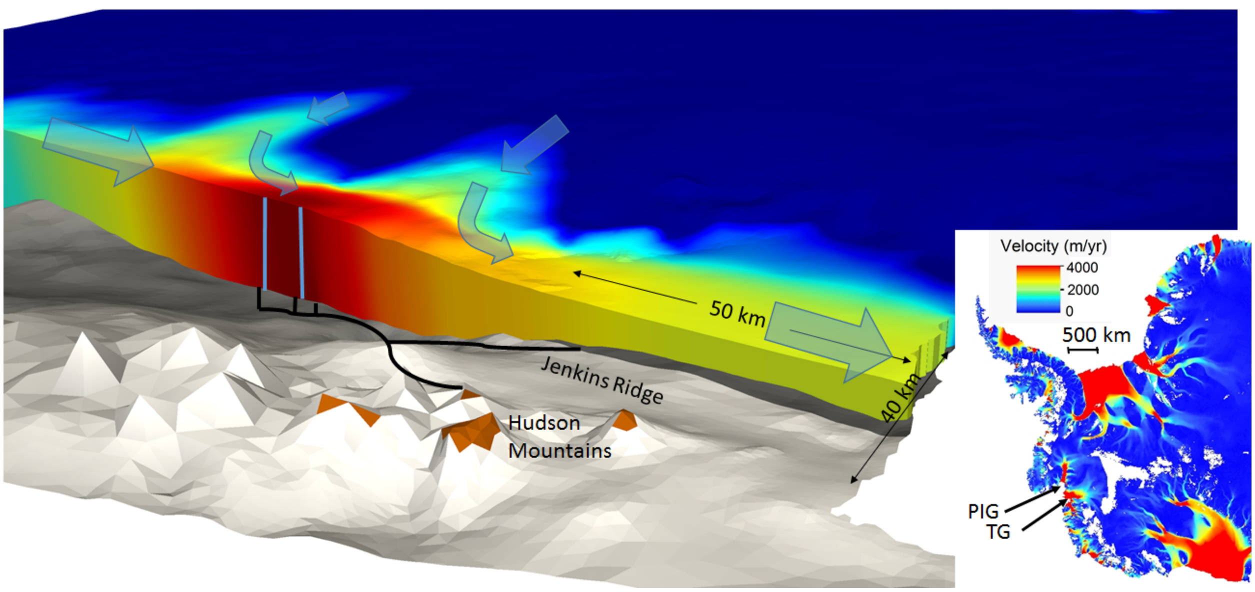

Fig. 2. A slice through the centreline of Pine Island Glacier (PIG), showing ice flow (blue arrows) with a 10×vertical exaggeration. The colours represent the dramatic simulated ice velocity slowdown in response to increased basal friction in a small part of the bed mimicking drying. Red colours indicate slowdowns of 4 km/yr while yellow and green are around 200 m/yr. Nunataks rising above the ice sheet are brown. The PIG grounding line is currently retreating from Jenkins Ridge at around 500m below sea level into an over-deepened trough more than 1

km deep. Model-based studies indicate that PIG is already undergoing irreversible retreat[4]. This retreat may be halted through geoengineering by 1) building a berm promoting re-grounding on Jenkins Ridge; 2) increasing basal resistance upstream of the grounding line – e.g. by pumping out subglacial water (cyan boreholes), diverting it to rock tunnels (black), or freezing it in situ. The inset of West Antarctica ice flow speed (white is no data), shows Thwaites Glacier (TG) and the view point for the main image of PIG.