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Could climate engineering save the Greenland Ice Sheet?

By Patrick J. Applegate and K. Keller, 1 September 2016

RESEARCH ARTICLE

Engineering the climate through albedo modification (AM) could slow, but probably would not stop, melting of the Greenland Ice Sheet. Albedo modification is a technology that could reduce surface air temperatures through putting reflective particles into the upper atmosphere. AM has never been tested, but it might reduce surface air temperatures faster and more cheaply than reducing greenhouse gas emissions. Some scientists claim that AM would also prevent or reverse sea-level rise. But, are these claims true? The Greenland Ice Sheet will melt faster at higher temperatures, adding to sea-level rise. However, it's not clear that reducing temperatures through AM will stop or reverse sea-level rise due to Greenland Ice Sheet melting. We used a computer model of the Greenland Ice Sheet to examine its contributions to future sea level rise, with and without AM. Our results show that AM would probably reduce the rate of sea-level rise from the Greenland Ice Sheet. However, sea-level rise would likely continue even with AM, and the ice sheet would not regrow quickly. Albedo modification might buy time to prepare for sea-level rise, but problems could arise if policymakers assume that AM will stop sea-level rise completely.

What is albedo modification? How does it work, and why is it risky?

Albedo modification (AM) is a possible technological solution to the problems caused by climate change, but it is also untested and risky. Many human activities that produce economic growth also emit greenhouse gases. These greenhouse gases cause surface air temperatures to rise because they trap infrared radiation near the earth's surface. Albedo modification interrupts this process by putting reflective particles into the upper atmosphere. Some of the sun's rays then bounce off these particles instead of warming the ground and the lower atmosphere, leading to reduced surface air temperatures. There are other possible climate-modifying technologies that could be called albedo modification, but injecting reflective particles into the stratosphere is the most commonly-discussed AM technique.

If it worked, albedo modification might reduce surface air temperatures faster and more cheaply than reducing greenhouse gas emissions. AM was partly inspired by volcanic eruptions, which also put reflective particles into the upper atmosphere and reduce surface air temperatures [P. J. Crutzen, 2006]. For example, the eruption of Mt. Pinatubo in 1991 reduced globally-averaged surface air temperatures by up to 0.5 C [D. E. Parker et al., 1996] [A. Robock et al., 2009]. Achieving a Pinatubo-sized reduction in surface air temperatures using AM might cost a few billion dollars per year [A. Robock et al., 2009]. This cost is a small fraction of the world's yearly economic output, which is trillions of dollars. On the other hand, producing a Pinatubo-sized temperature reduction via reducing greenhouse gas emissions would take much longer [D. Archer et al., 2009]. Substantial emissions reductions would carry large economic costs. Removing carbon dioxide from the atmosphere is even more speculative than AM and would likely be very expensive [K. Keller et al., 2008] [K. Z. House et al., 2011] [H. J. Schellnhuber, 2011].

However, temperatures would rise very quickly if albedo modification were initiated and then suddenly stopped [H. D. Matthews and K. Caldeira, 2007] [M. Goes et al., 2011]. The reflective particles only stay in the upper atmosphere for a few months or years, so new particles must be injected into the upper atmosphere continuously in order to maintain AM's benefits [A. Robock et al., 2009]. If a conflict or an economic crisis interrupted the delivery of new particles to the upper atmosphere, temperatures would rise quickly to the level they would have achieved if AM had never begun [H. D. Matthews and K. Caldeira, 2007]. This sudden increase in temperatures might be more disruptive to human societies than if nothing were done about climate change.

Albedo modification also comes with other important risks. We refer interested readers to Alan Robock's article, “20 reasons why geoengineering may be a bad idea,” for information on these additional risks [A. Robock, 2008].

Causes and consequences of sea-level rise

Greenhouse gas-driven climate changes increase flooding risks for people living near present-day coastlines through sea-level rise [A. Parris et al., 2012] [E. Spanger-Siegfried et al., 2014]. As surface air temperatures increase, glaciers and ice sheets melt more rapidly. The water from this melting ice runs into the oceans, raising globally-averaged sea level. The ocean also warms with the atmosphere, leading to additional sea-level rise through thermal expansion. Tides and storms can flood previously-protected areas when they stack on top of the long-term sea-level rise from melting glaciers and expanding ocean water [E. Spanger-Siegfried et al., 2014].

Could albedo modification prevent or reverse sea-level rise?

Some scientists have argued that, if sea-level rise is caused by surface air temperature increases, then a technology for reducing temperatures would also reduce sea-level rise. For example, a recent report by the US National Academy of Sciences “recommends an albedo modification research program be developed” [Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts et al., 2015]. This report discusses sea-level rise as a consequence of climate change, implying that AM could prevent sea-level rise. An opinion piece including one of the NAS report’s authors suggests that AM could help avoid “…major ice sheet collapse,” which would lead to large sea-level rise [D. W. Keith et al., 2010]. Another study concludes that AM could completely stop sea-level rise from the Greenland Ice Sheet [P. J. Irvine et al., 2009]. One study even argues that sufficiently strong climate engineering could reverse sea-level rise [J. C. Moore et al., 2010]. These studies arrived at their conclusions using computer models of the relationship between climate forcing and sea-level rise, and between temperature and Greenland Ice Sheet melt.

The great ice sheets and their contributions to sea-level rise

However, the ice sheets are an important unknown in predicting future sea-level rise, and the relationship between surface air temperature and ice sheet melt is complex. Small glaciers contain enough water to raise globally-averaged sea level by about 0.5 m [V. Radic and R. Hock, 2010], and thermal expansion could contribute perhaps a few meters to sea-level rise over the long term [J. A. Church et al., 2013]. On the other hand, if all the ice locked up in ice sheets melted, sea level would rise by about 70 m. Greenland holds ~7.3 m of this total amount, and the remainder is locked up in the Antarctic ice sheets [J. L. Bamber et al., 2013] [P. Fretwell et al., 2013]. This amount is many times the maximum contribution from all other sources.

The Antarctic Ice Sheets respond to ocean temperatures, not surface air temperatures. Air temperatures over Antarctica are so cold that the Antarctic Ice Sheets don’t lose much mass by surface melting. Instead, the Antarctic Ice Sheets lose mass by discharging solid ice into the oceans. The delivery of warm waters by ocean currents to the edges of the Antarctic Ice Sheets accelerates this process. One recent climate modeling study showed that albedo modification would not prevent warm waters from reaching the edges of the Antarctic Ice Sheets [K. E. McCusker et al., 2015].

It's also unclear that albedo modification would prevent sea-level rise from the Greenland Ice Sheet. Melting of the Greenland Ice Sheet depends on the size of the ice sheet, as well as surface air temperatures. The ice sheet collects fresh snow on its accumulation area, which is the high, cold part of the ice sheet's surface where snow that falls remains all year. It loses mass from its ablation area, which is the low, warm part of the ice sheet's surface where new snow partly or completely melts by the end of the summer. If the accumulation area shrinks relative to the ablation area, the ice sheet may continue to melt even if albedo modification causes temperatures to go down again.

Using a computer model to estimate future sea-level rise from the Greenland Ice Sheet, with and without albedo modification

What would happen to the Greenland Ice Sheet if albedo modification reduced surface air temperatures? Because ice sheets are complicated systems, we used a computer model of ice sheet behavior to answer this question [R. Greve et al., 2011]. The ice in the ice sheet flows under its own weight, moving ice from the center of the ice sheet toward the edges [R. B. Alley et al., 2010]. Ice sheets also collect snow and melt on their upper surfaces, slide over rock and sediment underneath, and discharge solid ice to the oceans along their edges. Sophisticated computer-based ice sheet models include all these processes.

Many other studies have used computer models to examine the behavior of ice sheets. In particular, a number of previous scientific papers examine the hysteresis behavior of ice sheets, in which the size of the ice sheet's response depends on the direction of the temperature change. However, these earlier studies do not tell us directly about albedo modification's potential effectiveness in reducing or reversing sea-level rise.

Climate scenarios with and without albedo modification

Models of the Greenland Ice Sheet need projections of future temperature change to estimate how much melt might happen on the ice sheet's surface, and therefore how much the ice sheet will contribute to sea-level rise [R. A. Bindschadler et al., 2013]. We estimated future temperature changes without albedo modification using an existing climate model simulation [J. Schewe et al., 2011]. Other scientists had already run a climate model far into the future, assuming that human activities put large quantities of greenhouse gases into the atmosphere. In this simulation, surface air temperatures over Greenland rose by about 11 C over the next few centuries. The world as a whole warmed by a much smaller amount, even in this somewhat extreme simulation.

Albedo modification has never been tested, and we can't be sure how governments or individuals might use it to control temperatures. To create scenarios of temperature change with AM, we assumed that AM could either prevent additional surface air temperature increases, or it could gradually return temperatures to present-day values. We called these two types of scenarios "stabilization AM" and "temperature drawdown AM," respectively. Both of these scenario types assume that AM is effective in changing surface air temperatures, and that the AM program is maintained for hundreds of years. We then ran the ice sheet model into the future using the different temperature scenarios.

What does the computer model say about albedo modification's effects on future Greenland Ice Sheet changes?

If greenhouse gas emissions are high and AM is not implemented, sea-level contributions from the Greenland Ice Sheet are small by the year 2100, but become large over the long term in our simulations. The ice sheet is clearly in trouble at the end of the present century, when the simulated rate of sea-level rise from the Greenland Ice Sheet is many times its observed present-day value. The ice sheet melts away almost completely by the year 3000, leading to a large increase in global mean sea level. In such a warm future, there would be additional sea-level rise from sources other than the Greenland Ice Sheet.

We assessed albedo modification's effects on sea-level rise by comparing our simulations that include AM to those that don't. These comparisons show that the rate of sea-level rise from the Greenland Ice Sheet is smaller with AM than without AM. However, melting of the Greenland Ice Sheet generally continues after AM begins. Also, the ice sheet does not grow back appreciably, even with AM.

Not surprisingly, the Greenland Ice Sheet's contributions to sea-level rise depend on whether AM draws down surface air temperatures, or simply stabilizes them. Temperature drawdown reduces the rate of sea-level rise more than does temperature stabilization. If AM stabilizes temperatures, the ice sheet continues to lose mass indefinitely. If AM draws down temperatures instead, the ice sheet shrinks for up to 150 yr before regrowing very slowly. The rate of regrowth is always a tiny fraction of the rate at which the ice sheet melts away before AM begins.

The ice sheet's size also affects albedo modification's ability to reduce sea-level rise from the Greenland Ice Sheet. Beginning temperature drawdown AM within the next few decades stops mass loss from the Greenland Ice Sheet. If AM begins later, the ice sheet is smaller and therefore already committed to additional ice loss.

How does our work relate to what other scientists have said?

Why did we get different results from other scientists who have studied this question? At least two earlier studies concluded that geoengineering would prevent or even reverse future sea-level rise. Geoengineering is a term that describes most methods for intentionally modifying the climate, including AM. One of these other studies used a very simple model of sea-level rise from all sources, driven by greenhouse gases and geoengineering [J. C. Moore et al., 2010]. However, this simple model is missing a key feature of the real Earth system. In this simple model, sea-level fall in response to temperature decreases is just as fast as sea-level rise in response to temperature increases. However, ice sheets melt much faster than they grow [J. D. Hays et al., 1976] [J. E. Hansen, 2007] [A. Grinsted et al., 2010]. Another study used a model of the Greenland Ice Sheet much like the one we used [P. J. Irvine et al., 2009]. However, this study's base scenario, with no albedo modification, involved smaller surface air temperature increases than ours. The Greenland Ice Sheet shrinks less, and is easier to "save" with AM, if surface air temperatures are smaller in the no-AM scenario.

Why do we have confidence in our results, and how could other scientists improve on our work? There are many computer models of ice sheet behavior that give different answers. The model we used accounts for most of the behavior of ice sheets, but it leaves out some processes that could cause the ice sheet to disappear more quickly. This simplified model runs quickly, allowing us to carry out the many long simulations required by our experimental design. If other scientists were to repeat our experiments with more-advanced ice sheet models, they would probably reach similar conclusions, even though their sea-level rise estimates might be higher or lower.

Other scientists could extend our work by investigating scenarios where greenhouse gas emissions are lower. Our model simulations are based on a scenario called "RCP 8.5," which assumes that world society makes relatively little effort to reduce greenhouse gas emissions. We refer interested readers to G. P. Wayne's "Beginner's Guide to Representative Concentration Pathways" [G. P. Wayne, 2013] for information on other potential scenarios.

Conclusions

Given the results above, albedo modification might not prevent sea-level rise, even if it has a strong effect on surface air temperatures. The Greenland Ice Sheet continues to contribute to sea-level rise in almost all of our simulations, even those that include AM. This additional sea-level rise could cause problems if planners assume that AM will completely stop sea-level rise. Because the ice sheet also regrows very slowly, AM will not simply restore the Greenland Ice Sheet to the way it was before large-scale greenhouse gas emissions began. However, albedo modification probably would reduce the rate of sea-level rise from the Greenland Ice Sheet. This slowdown could be beneficial if policymakers use the extra time to plan for more sea-level rise.

Acknowledgements

This work was partially supported by the National Science Foundation through the Network for Sustainable Climate Risk Management (SCRiM) under NSF cooperative agreement GEO-1240507 and the Penn State Center for Climate Risk Management. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Article information

Cite as: Patrick J. Applegate and K. Keller, Could climate engineering save the Greenland Ice Sheet?, *Climanosco Research Articles* **1**, 1 Sep 2016, https://doi.org/10.37207/CRA.1.10

ISSN 2673-1568
DOI https://doi.org/10.37207/CRA.1.10

Retrieved 3 Apr 2026
Version 1
In collection 1, Launch challenge

Authors

Patrick J. Applegate, Earth Sciences, Pennsylvania State University-Dubois / Earth and Environmental Sciences Institute, Pennsylvania State University
K. Keller, Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA

Categories

Climate of the future, Geoengineering, Ice & snow, Sea level, Arctic, Greenland

Metadata

Date of final publication 1 September 2016
Type of article: Focus article; Single source article (P. J. Applegate and K. Keller, How effective is albedo modification (solar radiation management geoengineering) in preventing sea-level rise from the Greenland Ice Sheet?, Environmental Research Letters, 10, 084018, 2015.)

Permanent url address:
https://www.climanosco.org/published_article/could-climate-engineering-save-the-greenland-ice-sheet/