Glacial Climate Intervention:
A Research Vision

Glaciological research should be expanded to include the science of ice-sheet preservation to determine if engineered interventions applied to critical ice-sheet regions may reduce sea-level rise.

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This document represents a white paper that articulates a perspective on future research directions based on discussions of glacial climate intervention held at workshops at the University of Chicago (2–3 October 2023) and Stanford University (9–10 December 2023), at an American Geophysical Union town hall (12 December 2023), and at a European Geosciences Union town hall (15 April 2024). Opinions expressed here are those of the authors only and do not necessarily reflect opinions held by all attendees of the workshops and town hall.

Executive Summary

Earth's two large ice sheets, in Antarctica and Greenland, are currently deteriorating and will continue to deteriorate even under the most optimistic greenhouse-gas emissions scenarios. They are a major contributor to sea-level rise and the subsequent damage to natural and human systems. We cannot stop sea-level rise, but we may be able to slow it while humanity does the necessary shift away from carbon-based energy systems.

Over the last four decades, scientific research on ice-sheet deterioration and sea-level rise has been focused on two essential questions:

1. **What physical processes cause ice-mass loss that contributes either directly or indirectly to sea-level rise?**

2. **How is climate change affecting these processes?**

Significant progress has been made on these scientifically (and logistically) challenging questions. Most notably, research has identified the physical instability processes that can accelerate ice-sheet mass loss leading to sea-level rise, even under steady or improving climate, as well as "hot spots" where instability may be happening now, e.g., the Thwaites Glacier in the Amundsen Sea sector of Antarctica.

Answers to the above questions have recently raised three further questions that are argued to be essential in driving research over the next two decades. These questions are:

3. **What natural processes might limit ice-sheet deterioration?**

4. **Are there human interventions that could enhance these natural processes, thereby slowing sea-level rise?**

5. **What is our window of opportunity for implementing these interventions?**

If there are technically feasible and socially acceptable interventions, they could greatly reduce the harm from sea-level rise. They would in no way reduce the imperative need to reduce fossil fuel consumption and all the other harms it causes (climate change, ocean acidification, storm intensification, droughts, floods, heat waves, wildfire, permafrost loss, etc.).

This document lays out a research agenda for answering these questions over the next decade, along with a consultation process for ensuring the transparency of the research and its relevance to future decisions about pursuing such interventions. The present document does not advocate for intervention; rather, it advocates for research into whether any interventions may be viable. It describes a pathway to identify possible interventions and the window of opportunity for pursuing them, assuming that the more quickly we know the research answers, the greater the opportunities will be, should any be viable. That window will also depend on the world's ability to reduce greenhouse gas emissions, thereby reducing pressure on glaciers. However, given the long residence timescale of carbon dioxide in the atmosphere and emissions already made, even the most optimistic reductions of future greenhouse gas emission, in the absence of either carbon dioxide removal or solar geoengineering used at sufficient scale to significantly reduce radiative forcing, will not prevent ice-sheet melt and attendant sea level rise.

Our proposal recognizes the additional pressures from thermal expansion of the oceans; ablation of smaller glaciers, ice caps, and the margins of the Greenland Ice Sheet; destabilization of Antarctica, with surface meltwater damaging the structural integrity of buttressing ice shelves. The proposed research also recognizes that destabilization of the Amundsen Sea sector of Antarctica is primarily driven by submarine, rather than atmospheric, melting; that the submarine melting has large natural inter-annual variability; and that glaciers in the Amundsen sector, including Thwaites and Pine Island may have already crossed a tipping point into unstable dynamic collapse, with self-reinforcing feedbacks involving grounding line retreat, ice flux, ocean-cavity volume, and basal melt rate, accelerating mass loss.

Onset of ice-sheet instability cannot be ruled out even under extremely aggressive emissions reductions

Ice-sheet instability is a function of the time-integrated effects of ocean and atmospheric warming. Time-integrated effects of warming on the Antarctic and Greenland ice sheets will thus persist regardless of how aggressively emissions are reduced in the future. This means that part of the ice-sheet-driven sea-level rise is essentially independent of future emissions scenarios. Therefore, research on glacial interventions may be applicable under the most optimistic future decarbonization pathways.

All research supports the intuitive logic that high, business-as-usual (e.g., the Representative Carbon Pathway, referred to as RCP8.5, that results in 8.5 W m^{-2} radiative forcing by 2100) greenhouse-gas emissions will accelerate Antarctic and Greenland ice sheet–driven sea-level rise. It is not clear, however, whether achieving the low-emissions scenarios or the international reduction pledges set out in the 2015 Paris Agreement and its updates would be sufficient to prevent or slow ice-sheet collapse driven by cumulative emissions to date. If the tipping point into dynamic collapse for parts of the Amundsen Sea sector of the West Antarctic Ice Sheet will soon be, or has already been, crossed, then future emissions scenarios will have little effect on preserving the ice sheet. Therefore, society may benefit from direct engineering interventions even in low-emissions scenarios.

The research agenda envisioned here recognizes that implementing an ice-sheet preservation intervention will be one of the more fateful decisions that climate change has forced upon world society. As a result, the vision outlined here reflects a new ethos that goes beyond the motivations that have guided glaciological research for decades. This ethos prioritizes a focus on the impacts of glaciological processes on the well-being of global societies, and it calls for robust participation of sociologists, humanists, ecologists, community leaders, scientific and engineering governing bodies, international treaty organizations, and other relevant stakeholders in guiding the research so that it provides the answers needed for informed decisions about interventions.

1.0 Introduction: Motivation for This White Paper on Glacial Climate Intervention

Two two-day workshops were convened in the autumn of 2023 to assess the state of knowledge on whether engineering interventions in Antarctica and Greenland could successfully slow sea-level rise. The first,[2] held in October 2023 at the University of Chicago, convened about 25 scientists, engineers, and students (see appendices B and D). The second workshop, held at Stanford University in December 2023, had roughly double that number (see appendices C and E). Both workshops discussed strengths and weaknesses of research into two prominent intervention proposals: (1) curtains moored on the seabed to block ocean-heat transport into critical sub-ice-shelf ocean cavities in the Amundsen Sea area of Antarctica, and (2) ice-sheet drilling to limit the thermal and hydrological factors at the subglacial beds of seaward-flowing ice streams. The Stanford workshop included "red teams," charged to search for weaknesses and areas of important ambiguity. In addition, the Stanford workshop produced a Workshop Report (https://doi.org/10.5281/zenodo.11115730) recommending a governance and oversight organization. Both workshops were conducted under the Chatham House Rule[3] and the Chicago Principles.[4]

The workshops were followed by a town hall meeting at the 2023 American Geophysical Union Annual Meeting (AGU23), where members of the Earth Sciences community at large were invited to comment on the idea of glacial climate intervention to reduce sea-level rise in general and the outcomes of the two workshops in particular. Like the two workshops, the town hall also considered questions of social license and justice, governance, ethics, and the wisdom of any research into glacial climate intervention.

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2 Funded by the University of Chicago as part of the University's Climate Systems Engineering Initiative (CSEi) founded in 2023.

3 The Chatham House Rule calls for opinions expressed during discussions not to be attributed to any individual discussant: https://www.chathamhouse.org/about-us/chatham-house-rule.

4 The Chicago Principles call for free and open discourse: https://freeexpression.uchicago.edu.

This document provides an unofficial summary of the workshops, drafted by some of the organizers and attendees (see appendices D and E for lists of the participants). It is intended to promote discussion within the scientific and policy community, including such leadership organizations as the Polar Research Board (PRB) of the National Academy of Sciences (NAS), the Secretariat of the Scientific Committee on Antarctic Research (SCAR), and other planning and funding agencies. It first summarizes current ice-sheet conservation research, including potential socially relevant negative effects (section 2) and then proposes research needed to inform societal decision making and its governance (section 3).

Principles for evidence-based debate

The idea of performing scientific research on glacial climate interventions is viewed with a variety of diverse opinions that will undoubtedly generate debate. While not discussed at length at either of the workshops or town hall, the necessity of keeping the debate both productive and civil is universally recognized. One way to engender effective, respectful debate is to adhere to principles that maintain a focus on scientific evidence, the difference between scientific knowledge gain and actual deployment, the inclusion of all points of view, and the diversity of participants. Below are eight such principles.

1. **Civility and respect**. All participants in this debate, regardless of their point of view or background, should be treated with respect. Arguments should be engaged on their merits without ad hominem attacks or other disrespectful behavior.

2. **Transparency, not secrecy**. Research, and the debate it creates, should be done and reported in the open. Debate should be directed toward the greater good and not toward parochial interests.

3. **Value caution**. Research conducted under the typical social pressures of the present day tends to emphasize successful, positive outcomes and achieves greatest attention when it achieves impactful, significant results. Scientific research on glacial interventions must also emphasize shortcomings, failed ideas, and dead ends, because so much is at stake.

4. **Research is not implementation and does not imply support for implementation**. There must be off-ramps and failure points identified to abandon an idea if necessary as soon as possible, so that there is no "slippery slope."

5. **Examine risks of not doing an intervention as well as risks from any intervention**. There is no sense in comparing with the present, because we are not in steady state.

6. **Treat uncertainties fairly**. We do not know everything about an intervention, but we also certainly do not know how to recognize early stages of ice-sheet collapse. The Precautionary Principle tells us that uncertainty is not an excuse to delay research. Decisions must be taken on the best available evidence at the time they need to be made. Any sensible intervention must be as reversible as possible.

7. **Normalize research on these interventions**. This does not mean approve them, but it does mean discuss them rationally. Any large social change entails normalization, whether a socio-technical innovation—like the spread of the automobile—or a moral advance like the extension of rights to previously excluded groups or the recognition of environmental limits to human activities. It is about moving from a taboo into mainstream discussion for evaluation.

8. **Make sure governance is inclusive**. Stakeholders on sea level in the Global South (and Arctic) need participation in any research—they have a right to know what tools may be in the box and not be "spoken for" by the developed world (or the Antarctic Treaty System). This also implies that research must be reported in open-access forums, with emphasis on transparency in who is doing the research and how it is funded.

2.0 Current Standing of Ice-Sheet Conservation Research

Glacial climate interventions seek to slow human-induced disintegration of ice sheets so as to slow sea-level rise. If successful, these interventions would protect social and ecological systems around the world (e.g., ports, agriculture, and wetlands), with some of the greatest benefits to some of the most vulnerable communities (e.g., Pacific Island nations and heavily populated deltas). From an economic perspective, the costs and benefits of these interventions would have to be weighed against the costs and benefits of larger individual engineering interventions at thousands of coastal locations around the world—decisions that will need to consider the complex, uneven distributions of costs and benefits, depending on how they are funded and executed. There are many analyses of dispersed responses to sea-level rise. There is limited scientific and economic understanding of glacial interventions, particularly regarding large-scale ice-sheet deterioration (most notably that caused by the marine ice-sheet instability, or MISI) associated with ice streams and glaciers in Antarctica and Greenland. For example, the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6) projects with confidence sea-level rise rate and level at 2100 as 4–8 mm/year and 40–80 cm, respectively, based on present-day trends. However, it cannot rule out much faster and larger sea-level rise, given uncertainty about present and future marine ice-sheet instability.

By all accounts, worst-case scenarios for sea-level rise depend on what happens in one specific region of the Earth: the Amundsen Sea sector of Antarctica. Thus, a technically feasible and socially accepted intervention there could have global benefits. We have a strong scientific foundation for analyzing the threat and opportunity, based on decades of research answering questions 1 and 2 above (in the Executive Summary). We now need answers to questions 3–5 (in the Executive Summary).

Glaciologists have been informally discussing interventions since the early 1980s, when the community first began realizing the potential effects of global climate change on the marine ice-sheet instability process, concurrent with the first discoveries of how ice streams and ice shelves behave and interact. Since then, the growing science base has included basic research on paleoclimate, ice-sheet mechanics, and remote-sensing exploration. Peer-reviewed research, with numerical models for alternative interventions, began to emerge in the 2010s. Most involved ways to adapt natural mechanisms that affect ice streams and glacier stability.

The sections below briefly summarize two prominent approaches, which we will call (1) ***ocean-heat transport interventions*** (section 2.1) and (2) ***basal-hydrology interventions*** (section 2.2). We also note other proposed interventions, notably (3) ***seawater pumping interventions*** (section 2.3). For readability, this document does not cite the supporting literature in the normal academic manner; rather all citations are contained in the bibliography that forms appendix A. After summarizing the prominent approaches to ice-sheet preservation, we highlight some of the possible negative side-effects of these interventions (section 2.4). In section 3, we list steps that are needed to support our vision of future research activity. In section 4, we conclude this white paper by reiterating the rationale for immediately expanding research efforts on ice-sheet preservation interventions.

2.1 Ocean-Heat Transport Interventions

One of the most striking contrasts in Antarctica’s response to climate change is between ice streams that discharge into large, mechanically strong ice shelves that float in water at the sea-surface freezing point (-1.9°C) with ice streams that discharge into small, constantly disintegrating ice shelves that float in water influenced by circumpolar deep water (CDW), making it much warmer (e.g., up to +2°C, or approximately +4°C thermal forcing above the melting temperature). Both the Ross and Ronne-Filchner ice shelves are underlain by cold water and show relatively little imapact of climate change. These ice shelves are thus able to maintain stability in the ice streams they buttress. In contrast, the ice streams flowing into the Amundson and Bellingshausen seas are buttressed by small ice shelves that have high basal melt rates due to the warm water below them. These ice streams include the Thwaites and Pine Island glaciers, which have the greatest signs of unstoppable, accelerating discharge, and which could cause several meters of sea level rise in one or more centuries.

One possible way to prevent the demise of the Thwaites and Pine Island glaciers: stop the warm circumpolar deep water from circulating under their fringing ice shelves, as happens naturally at fjord mouths or by shallow bathymetry on continental shelf edges. Initial conceptual studies suggest that this could be accomplished by setting sediment berms or fibrous curtains along the seabed in the front of ice shelves so as to block the flow of circumpolar deep water and encourage sub-ice-shelf cavities to fill with the cold water formed closer to the coastline by wintertime sea-ice formation. In essence, the plan is to make the environment at the fronts of the Amundsen Sea glaciers more like the environment at the front of the ice streams that flow into the Ross Ice Shelf. If the intervention works, the reduction in water-column temperature would reduce the basal-melt rate underneath the floating ice shelf, and the iceberg calving rate as well. These changes would, in turn, cause the ice shelf to thicken and lengthen, leading to regrounding on bathymetric pinning points and an increase in the buttressing force that resists ice flow across the grounding line. This would stabilize the ice sheet and slow the rate of collapse. Modeling studies show that even modest curtains, covering a fraction of the water-column height at the deepest channel entries to the Amundsen Sea coast, could slow sea-level rise from melting of these glaciers by a factor of 10.

2.2 Basal-Hydrology Interventions

A very different intervention is suggested by another natural process: the shutdown (sudden stop) of the Kamb Ice Stream's flow approximately 200 years ago. That event shows that ice streams can decelerate as well accelerate. Better understanding of why the Kamb Ice Stream shut down of its own accord will tell us whether there are human interventions that could make it happen again.

A decade of research has focused on how subglacial hydrology and sediment conditions vary among the ice streams along the Siple and Gould coasts of the Ross Sea sector of West Antarctica. Researchers have found that the Kamb Ice Stream shutdown occurred at a time when the bed became drier. Reducing the water content of the basal sediments increased friction between the ice sheet and basal sediments, slowing the ice stream until it eventually stopped. Thus, the reduction in basal lubrication initiated a positive feedback process, wherein the slowdown in ice flow reduced the rate of shear heating, leading to the loss of subglacial water through freezing, which then slowed the ice further. Sequences of refrozen basal meltwater with entrained basal sediments can be observed in boreholes at the base of the stagnant Kamb Ice Stream today.

The initial cause of this basal drying is thought to be the encroachment of the ice stream next to the Kamb Ice Stream: the Whillans Ice Stream. It has been growing headward with tributaries that extend their reach upstream. This headward growth eventually intersected with the catchment region of Kamb Ice Stream and provided a hydrologically favored path for water to move toward the ice sheet margin. In effect, the Whillans Ice Stream "pirated" the water that was lubricating the bed of Kamb Ice Stream, causing it to shut down.

The idea of artificially intervening in ice-stream and glacier flow is to mimic the shutdown of Kamb Ice Stream. This would be done by finding a way to remove water from the bed of the ice stream to decelerate its flow. One possible intervention with this aim would create a "drill field" with multiple access holes to the subglacial bed, and these holes would be used to extract either water or heat from the subglacial system, possibly using passive, unpowered thermosyphons. An alternative strategy would introduce naturally self-maintained subglacial pathways, such as canals and tunnels, that reduce hydrological resistance to water moving quickly from the subglacial bed to the ocean beyond the ice sheet.

One of the advantages of basal-hydrology interventions is that there is little or no endemic biosphere below active ice streams. Interventions undertaken in the subglacial environment would have much less ecological impact than those involving seabed constructions designed to block ocean-heat transport. Microbiological research on subglacial environments is a relatively new field, thus more inquiry remains to be done to verify the ecological advantages of basal-hydrology interventions.

2.3 Other Interventions

While the previous two interventions were the primary foci of the UChicago and Stanford workshops, other interventions have been suggested. Most have been little-studied to date. They include using windbreaks to interrupt blowing snow and increase mass deposition, using cables and anchors to delay rifting and breakup of floating ice shelves, adding reflective materials to the ice surface to reduce ablation, and draining melt ponds laterally over the ice sheet surface to prevent their draining downward to the bed. The latter two ideas would be better suited to marginal areas of Greenland, where surface ablation is an important part of the mass budget, rather than West Antarctica.

One additional intervention idea has received research attention, but was not a focus of the two workshops. It would increase the surface mass balance of the ice sheet by pumping seawater onto the ice surface, where cold air temperatures would cause it to freeze in place, especially in wintertime. While the other two intervention strategies focus on the outflow of ice-sheet mass, seawater pumping interventions would modify the inflow, restoring the ice sheets by transferring seawater to them. These strategies for countering the marine ice-sheet instability would be somewhat similar to ocean-heat interventions: increasing rates of mass deposition near the grounding line would increase mass flux across the grounding line, which in turn would increase the thickness and extent of the floating ice shelf, causing regrounding on pinning points, an increase in buttressing force, and a reversal of the dynamic instability. Work on these interventions has focused on Antarctica, rather than Greenland or elsewhere, because its colder surface conditions are better for freezing pumped seawater and because there is less concern for local ecology and human settlements. These interventions have been proposed both for adding bulk mass to slow-flowing parts of East Antarctica in order to counteract losses elsewhere and also for adding mass to vulnerable areas of the Amundsen Sea sector of West Antarctica, countering the marine ice-sheet instability. The energy requirements of seawater pumping interventions would be enormous.

2.4 Adverse Impacts and Unexpected Behaviors

Although some initial progress has been made on scientific and engineering aspects of these interventions, each has significant uncertainties. Moreover, the negative and positive ecological, social, and economic effects have received little attention to date. Research on these potential impacts is an essential part of the vision proposed here. This is challenging research, given the remoteness of the sites and the pressures of climate change. We can, however, sketch illustrative issues focusing only on a few of the possible negative impacts.

- For ocean-heat interventions, heat blocked from the sub-ice-shelf cavities may have effects all along the Amundsen Sea coast. For example, if the circulation of warm circumpolar deep water shifts west, it could affect other ice shelves, potentially reducing their stability, while changing local ecology in uncertain ways.

- For basal-hydrology interventions, reducing ice flux into the grounding zone might accelerate grounding line retreat if submarine melt rates remain high.

- For seawater-pumping interventions, placing seawater on the surface of an ice shelf can cause flexural strains and stresses that induce fractures that accelerate instability, as happened with the collapse of the Larsen B Ice Shelf in 2002. The salinity of the seawater might produce brine layers that damage the structural integrity of the ice. The energy requirements for pumping large volumes of seawater pose unsolved problems.

All glacial climate interventions are scientifically new and not yet proven to work, and are technically and socially complex projects with multiple uncertain impacts. Research on all these dimensions must proceed in parallel for successful proposals to come together and for unsuccessful proposals to be abandoned with timely off-ramps. Their evaluation must consider local and global costs and benefits, for human and environmental systems under complex, uncertain pressures from climate change.

Common arguments against glacial interventions

A number of well-reasoned objections to the conduct of scientific research on glacial interventions are forcefully argued within the glaciological community. Some of these objections are projected onto the question of scientific knowledge gain by conduct of research from the real target, consisting of the actual implementation of a glacial intervention. Several of these objections are listed below.

1. **Scientific knowledge developed on glacial interventions could disincentivize greenhouse-gas emissions reduction**. The politics of climate change is fraught with denialism. Some scientists in our community argue that by developing the ideas that underly a technology to reduce sea-level rise will be used to falsely justify the notion that greenhouse-gas emissions need not be reduced as quickly as called for by, for example, the 2015 Paris Agreement.

2. **Undue reliance on technological fixes**. The existence of scientific knowledge on glacial interventions may lead to complacency or even disregard of exposure to sea-level rise. Communities that have undue reliance on unproven technological fixes may delay adapting in other necessary ways to oncoming sea-level rise. People may be lured into building infrastructure and housing in areas that may increase exposure to the hazard of sea-level rise.

3. **Unintended, adverse, and unforeseen consequences**. Glacial intervention has never been tried before, hence if it is tried in the future, there will be a high probability of environmental and social consequences that are unforeseen and which could be adverse. Indeed, all forms of mitigation and adaptation to sea-level rise, including coastal engineering on a massive scale, will have

unforeseen and possibly adverse consequences. Generally speaking, more scientific research on such engineering and/or interventions is the only way to address such consequences.

4. **Moral hazard**. This refers to (a) the current generation of scientists making decisions the risks of which are experienced by future generations and (b) powerful nations making decisions that will impact less technologically and economically developed nations. A key consideration is whether avoiding research on glacial intervention now will deny or delay giving future generations and less-developed nations as much glaciological knowledge as possible in case they need it.

5. **Social justice and governance**. The decision to research and potentially deploy glacial intervention is likely to be made by developed nations and may be optimized toward satisfying their own interests. This raises a social justice issue that must be carefully understood and managed through an inclusive governance system.

6. **Diversity, equity, and inclusion**. Currently, the scientific community that engages in both research and debate on or about glacial intervention is small. This means that a full range of perspectives and insights is missing from the conversation. Understanding the historically contingent interaction of geographic, demographic, and cultural identities with economic and political institutions, and the ways that those institutions can either promote or impede resiliency, is critical to understanding how the actual impacts of ice-sheet-driven sea-level rise will play out in local communities.

3.0 Research Vision: What Should Be Done?

This white paper is meant to serve as a catalyst for action by the scientific community and its leadership. We believe that a major initiative is needed, with these properties:

1. **Vigorous debate of the ethical, social justice, and governance aspects of glacial climate interventions**. Human interference into any kind of natural process is fraught with moral and physical

hazards. We need vigorous public debate of potential benefits and harms, informed by research that creates evidence regarding those concerns. We need to know and discuss how such interventions will affect people across the globe, natural systems, perceptions of “nature,” and pressure to reduce anthropogenic climate change. Without emission reductions, even successful glacier interventions will only buy a little time. Although these deliberations should be informed by science, their resolution is ultimately a political and ethical question. We recommend that the people who perform this debate should be experts in those domains, with glaciologists as secondary actors—translators at most.

2. **Engagement of scientific leadership in deliberative, exploratory consideration of glacial climate intervention**. As an initial step, we recommend that the Polar Research Board of the US National Academy of Sciences convene a panel of experts charged with writing a consensus report complementing the report “Future Directions for Southern Ocean and Antarctic Nearshore and Coastal Research” (2023, The National Academies Press. https://doi.org/10.17226/27160). The report would assess the benefits and risks of adding ice-sheet conservation research to those programs. Like other National Academy of Sciences panels, it would include scientists with a range of opinions and expertise regarding the issues raised in this white paper. The report produced by the panel of experts convened by the Polar Research Board should address “what” and “how” to study, not “whether” to study, as expertise in polar science does not cover questions of “whether.”

3. **Engagement of the scientific community in concept testing of glacial climate intervention**. Members of relevant disciplines should initiate workshops and paper sessions at national and international meetings (e.g., the American Geophysical Union, the European Geosciences Union, the International Glaciological Society, the International Association of Cryospheric Sciences, the Arctic Research Consortium of the United States, the Association of Polar Early Career Scientists, etc.) to create a community of

researchers either directly engaged in glacial climate intervention research or willing to provide perspectives and feedback. We note that engagement in this research does not imply support for implementation. We encourage the transparent, self-critical format of the University of Chicago and Stanford University workshops and the 2023 American Geophysical Union (AGU) town hall meeting. These community meetings will bring together what we know and provide forums for designing and discussing future research, along the lines of the meetings that have promoted research on the West Antarctic Ice Sheet since the early 1980s.

4. **Engagement of the engineering community with existing or future technologies that might address, and welcome, these challenges**. While scientific research can identify needed interventions and public consultation can identify socially acceptable ones, only engineering analyses can identify technically feasible ones and estimate their costs. The rigorous conditions of Antarctica will need civil, marine, and environmental engineers to analyze potential projects and adapt or invent technical solutions. Much of that expertise lies in commercial firms working in extractive industries. Engaging them could present both challenges and opportunities. Tight coupling will be needed to ensure that science, engineering, and consultation proceed in tandem. One possible model of such engagement is the recent effort to connect Antarctica to the internet via a submarine cable.

5. **Engagement of stakeholders locally and internationally, to have diverse perspectives throughout the process**. The project should follow established protocols for proactively engaging local stakeholders, such as the standard of free, prior, and informed consent (FPIC) pursued by such representative bodies as the government of Greenland and the Inuit Circumpolar Council. These standards respect the rights, cultures, and knowledge of these residents in maximizing benefits and minimizing damages. Given the global implications of sea-level rise, the process should engage representatives of small island nations and vulnerable coastal regions. Given the potential effects on ecosystems, ecologists

and environmental organizations should be engaged as well, as stewards of the ice sheet. Those engagements should include continuing, transparent, two-way communications, collaborating with locally trustworthy intermediaries.

6. **Engagement of the Secretariat of the Scientific Committee on Antarctic Research**. The project must respect Antarctica's strong environmental protection in international law. It is governed most directly by the 29 voting members of the Antarctic Treaty System (ATS), framed by the Madrid Protocol (1988), calling for Antarctica to be governed "in the interest of mankind as a whole." Although unanimity is required for many decisions, the Antarctic Treaty System has repeatedly proven able to rise to challenges, as when addressing concerns of states most threatened by sea-level rise accelerated by the collapse of Antarctic ice sheets. The Scientific Committee on Antarctic Research, established by the Antarctic Treaty, helps set research agendas and coordinates with international bodies, such as the Intergovernmental Panel on Climate Change. Individual states enact Antarctic Treaty System provisions through domestic law (e.g., the United States Antarctic Conservation Act enforces environmental permitting requirements of the Madrid Protocol for US nationals). While early research into ice-sheet stabilization might readily proceed under the present system, future developments may require standing multinational bodies under the aegis of existing agreements.

7. **Establish a research agenda to investigate how ice-sheets will respond, either intentionally or collaterally, to other forms of climate intervention.** While not discussed in this document, there are a wide variety of approaches being considered to address climate change and its impacts in other areas. For example, there are various technologies being considered to remove carbon dioxide from the atmosphere at a large scale (CDR) and to manage the solar radiation budget regionally or even globally (SRM). The principal focus in this document has been on interventions in the local glacial environment; however, future research should acknowledge the development of other climate intervention techniques and strategies. It is essential that

glaciological research proactively evaluate the consequences, both beneficial and deleterious, of other climate intervention approaches.

4.0 Conclusion: To Where Should Glaciological Science Evolve?

In 1990, when the Intergovernmental Panel on Climate Change first assessment report (FAR) was released, global CO2 emissions were ***22.8 billion metric tons per year*** and atmospheric CO2 concentration was ***354.5 ppm***. Today, the figures are ***37.6 billion metric tons per year*** and ***421.9 ppm***, respectively. These metrics indicate that the world has done little to slow the emission of CO2 in the 34 years since the first official report of the Intergovernmental Panel on Climate Change. Climate-system inertia guarantees that the consequences of these emissions will be with us for generations, as will those occurring even with the most ambitious feasible emission mitigation efforts.

That first assessment report by the Intergovernmental Panel on Climate Change raised the specter of accelerating glacier melt propelling accelerated sea-level rise, with catastrophic global consequences. In the ensuing decades, research into the two basic questions that opened this white paper (see the Executive Summary) has had the unexpected practical benefit of uncovering a catastrophic threat to global well-being: dynamic collapse of portions of the Antarctic Ice Sheet, accelerating sea-level rise and the attendant damage to human and natural systems. Deep uncertainties remain about the timing and rate of potential ice-sheet collapse, producing correspondingly deep uncertainties in our knowledge of the human impacts of that collapse. Yet that basic research has also identified potential solutions, whose global return on investment might be enormous, but which may have effects that could induce further catastrophes. We see an urgent need to examine these solutions while the window of opportunity for possible deployment is still open.

Of course, basic research addressing the first two questions (see the Executive Summary) remains urgently needed if the people of the world are to prepare for their shared future. Yet, new research, focused on the three new questions that opened this white paper (in the Executive Summary), is also needed if we are to evaluate options for reducing that threat. Some of that investment will involve basic research focused on the topics discussed here, observing and modeling glacier, ocean, and biological systems. Some of that will be basic natural research creating the foundations for potential interventions (e.g., ice-stream movement, ecological effects of salinity changes). Some will be basic research involving novel collaborations with social and engineering scientists. Some of the investment, though, will be largely practical: adapting and testing equipment, project management and negotiations, consultation and communication.

It will take time to lay the scientific, engineering, and social groundwork for ice-sheet preservation interventions. It will take more time to begin to reap their sustained benefits, should they exist. During all that time, ice sheets will continue to melt, discharging mass across grounding lines and inducing sea-level rise. Without research, we cannot know if there are viable interventions. Without the concurrent practical planning, engineering, and consultation, there will be an unconscionable delay in action, should there be a solution. Such big science and engineering would entail a major expansion of glaciological research and its integration with other scientific, engineering, social, and governance bodies. We are proposing such an ambitious program because we see examining options for reducing sea-level rise from ice-sheet melting as a global imperative.

Appendices

A. Bibliography

B. Chicago Workshop Agenda

C. Stanford Workshop Agenda

D. Participants of the Chicago Workshop

E. Participants of the Stanford Workshop

F. Acknowledgements

Appendix A. Bibliography

Overview

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Ethical Frameworks for Climate Intervention and Other Web Resources

AGU website containing principles, comments and a white paper: https://www.agu.org/learn-about-agu/about-agu/ethics/ethical-framework-for-climate-intervention

EGU blog on "Geoengineering and (un)making the world we want to live in": https://blogs.egu.eu/geolog/2013/07/31/geoengineering-and-unmaking-the-world-we-want-to-live-in/

The "Oxford Principles" on geoengineering: http://www.geoengineering.ox.ac.uk/www.geoengineering.ox.ac.uk/oxford-principles/principles/

Funding principles at the Harvard University Solar Geoengineering Research Program: https://geoengineering.environment.harvard.edu/funding

Brookings Institute Recommendations on Geoengineering to the Biden Administration: https://www.brookings.edu/articles/preparing-the-united-states-for-security-and-governance-in-a-geoengineering-future/

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The Siege of Miami by Elizabeth Kolbert: https://www.newyorker.com/magazine/2015/12/21/the-siege-of-miami

Website for the Energy Policy Institute of Chicago at the University of Chicago: https://epic.uchicago.edu/

Lecture delivered by Prof. Michael Oppenheimer, “Sea level rise, Part II: how can we adapt?”: https://epic.uchicago.edu/events/event/michael-oppenheimer-sea-level-rise-part-ii-how-can-we-adapt/

An IGS Global Seminar Series talk: “The Greenland Ice Sheet and Stratospheric Aerosol Geoengineering” https://www.youtube.com/watch?v=S6NAAnU_6xE

An article about sea-walls as a protection against sea level rise from the New Yorker Magazine: https://www.newyorker.com/news/annals-of-a-warming-planet/can-seawalls-save-us?_sp=9b96180b-7c11-479b-bd43-fe8066e8aab8.1712261707943

The Financial District and Seaport Climate Resilience Master Plan of New York City: https://www.nyc.gov/site/lmcr/progress/financial-district-and-seaport-climate-resilience-master-plan.page see also: https://e360.yale.edu/features/new-york-city-climate-plan-sea-level-rise

A collection of New Yorker Magazine articles about the control of nature, including by acclaimed author John McPhee: https://www.newyorker.com/magazine/the-control-of-nature/page/2

National Security Memorandum on United States Policy on the Antarctic Region, The White House, 17 May 2024. Published online. https://www.whitehouse.gov/briefing-room/presidential-actions/2024/05/17/national-security-memorandum-on-united-states-policy-on-the-antarctic-region/

The Chicago Principles on free expression and open discourse: https://freeexpression.uchicago.edu

The Chatham House Rule: https://www.chathamhouse.org/about-us/chatham-house-rule

Appendix B. Chicago Workshop Agenda

Workshop Motivation

The Intergovernmental Panel on Climate Change sixth assessment report projects that sea level will rise by 0.5 m to 1.0 m by 2100, with a low-likelihood, high-impact possibility of 2.0 m. Furthermore, sea level will not stop rising after 2100, even if emissions are reduced. Sea-level rise beyond 2100 could amount to meters scale, especially if parts of Antarctica and Greenland are destabilized by processes happening today and over the next 80 years.

Sea-level rise threatens to impact valuable economic infrastructure (some say amounts to $30 trillion worldwide) that contributes to human livelihood and socioeconomic security. It also impacts ecosystems and the stability of landscape flora and fauna. In some cases, sea-level rise threatens homelands and could instigate human conflict and suffering arising from migration.

Motivated by the hazards of projected sea-level rise, the workshop is convened to discuss one type of response to the hazard. (By far the most effective response, of course, is to stop emitting greenhouse gases to the atmosphere.) The questions of how to preserve ice volume in Greenland and Antarctica through technological interventions at or near key areas of these two regions will be the subject of the workshop. Loss of Alpine glaciation and stearic expansion of the ocean also affect sea level, but will not be considered by the workshop.

Workshop Objectives

The workshop intends to facilitate in-depth discussion of the scientific basis for variously proposed technologies and schemes for intervening in ice loss from Greenland and Antarctica. Examples of leading schemes include blocking ocean-heat transport to grounding lines with underwater curtains and subglacial hydrologic intervention through drilling. The goal is to identify what artificial controls may have sufficient scientific merit to justify further scientific research and to define specific research pathways that will yield the greatest understanding. The workshop is primarily ***not*** intending to determine whether any particular scheme, or any scheme in general, is *advisable, politically practical, or ethical*. There will be a short opportunity at the workshop to discuss these questions and to determine possible venues for their in-depth discussion in the future.

Outputs of the workshop will be, foremost, the generation of scientific discourse on the subject by leading scientists from around the world. Also to be produced is a "white paper" outlining the results of the workshop discussion on future scientific research and other activity needed to explore glacial engineering schemes. This white paper will be circulated to various public bodies, including the National Academy of Sciences Polar Research Board, the Secretariat of the Antarctic Treaty, the Scientific Committee on Antarctic Research, and various leadership councils of indigenous communities of the Arctic. A workshop report will be prepared for publication in a journal such as the American Geophysical Union's *Eos* newsletter.

Workshop Agenda:

Sunday, October 1, 2023

5:00–9:00: Welcome reception at Truth Be Told
(located in The Study hotel)

Monday, October 2, 2023

8AM: Breakfast, Rubenstein Forum
(next to The Study hotel)

9AM: Introduction

- UChicago Climate Systems Engineering Initiative Overview

- Workshop Overview
- Goals of Workshop
- Guidelines for Discussion

10AM: Keynote on Ocean Heat Flux Interventions

10:30AM: Discussion
- 30 minutes: Scientific Basis for Idea
- 20 minutes: Points of Potential Failure
- 20 minutes: Metrics of Success and Viability
- 20 minutes: Scientific Paths Forward

12PM: Lunch, Rubenstein Forum

1:30PM: Keynote on Subglacial Environment Interventions

2PM: Discussion
- 30 minutes: Scientific Basis for Idea
- 20 minutes: Points of Potential Failure
- 20 minutes: Metrics of Success and Viability
- 20 minutes: Scientific Paths Forward

3:30PM: Break, Rubenstein Forum

4PM: Discussion on Key Problems to be Addressed (Scientific, Decision Criteria, Ethical)
- 45 minutes: Knowledge co-production and Environmental/Societal Impacts
- 45 minutes: Governance and Financing Structures
- 30 minutes: Role of Academic Science

5:30PM: Adjourn

6:00PM: Viewing of Smart Museum Exhibit on the art of Ruth Duckworth, "Life as a Unity", Regenstein Library. Optional visit to view Henry Moore "Nuclear Energy" Sculpture Plaza. (https://news.uchicago.edu/story/ruth-duckworths-clouds-over-lake-michigan-will-have-new-home-uchicago) and (https://en.wikipedia.org/wiki/Nuclear_Energy_(sculpture))

6:30PM: Buffet Dinner, Quadrangle Club

Tuesday, October 3, 2023

8AM:	Breakfast, Rubenstein Forum
9AM:	Overview of schemes yet to be explored
9:15AM:	Breakout Discussions: Other Ideas/Brainstorm – 45 minutes: Scientific Basis for Other Ideas – 30 minutes: Brainstorm of Other Options
10:30AM:	Break
11AM:	Breakout Discussion on Roadmap Forward
11:45AM:	Structured Group Discussion on Roadmap Forward
12:30PM:	Lunch, Rubenstein Forum *(12:30 PM onward: attendees are welcome to begin homeward travel)
1:30PM:	Discussion of "white paper" and workshop report(s) to be written over the next 3 weeks
5:30PM:	Adjourn
6:30 PM:	informal dinner (those remaining for the night of 3 October are welcome to make their own arrangement or dine at Truth Be Told or Bar Dan, both located near hotel)

*The workshop organizing committee will monitor situations that may arise from the expected Government Shutdown to begin roughly during the first few days of October. Should the situation merit, workshop attendees who will be traveling Tuesday afternoon or evening will be assisted in making arrangements to get to the airport with extra time to allow for TSA slowdown.

Website for the Rubenstein Forum: https://davidrubensteinforum.uchicago.edu/

Announcement of the new University of Chicago Climate Systems Engineering Initiative (CSEi): https://news.uchicago.edu/story/david-keith-joins-university-chicago-lead-climate-systems-engineering-initiative

Appendix C. Stanford Workshop Agenda

Exploratory Antarctic Ice Loss Intervention Workshop

December 9 & 10, Stanford University

Summary:

The Exploratory Antarctic Ice Loss Intervention Workshop, December 9-10 at Stanford University, will gather 40+ world renowned glaciologists to evaluate potential ways to slow down the loss of Antarctic glaciers, focused on the Thwaites and Pine Island glaciers. The meeting will explore real-world tests to evaluate the technical feasibility of proposed interventions (*e.g.*, subglacial water pumping, sea curtain temperature management, surface albedo modification). Participants will pool their knowledge about these interventions and identify research required to reduce critical uncertainties. The organizers view technical feasibility as necessary, but not sufficient for the social acceptability of any such interventions. Organizers are planning future meetings convening a broad set of stakeholders whose voices will inform the scientific discovery process related to Antarctic climate interventions.

(Note: several diagrams and figures have been removed from the Stanford agenda document to avoid complexities associated with meeting Americans with Disabilities Act (ADA) standards.)

Workshop Objective:

Detailed plans and next steps to answer the questions:

Is there a technically feasible Antarctic Ice Loss Intervention that is worth pursuing?

- How big of an impact could it have?
- What are chances it could be accomplished in time?
- What do we need to learn to answer these questions?

<u>Rough Schedule outline:</u>

Saturday Workshop: Location Stanford Design School

9:00–9:30:	Coffee, Pastries & Fruit
9:30–10:30:	Workshop Intro, objective & process, Guidelines, Summary of Chicago Workshop
10:30–11:30:	Short presentations – Seabed curtains – Subglacial – Other ideas - 30 second pitches
11:30–12:00:	Post it note exercise, brainstorming
12:00–13:00:	Lunch conversations
13:00–14:30:	**Wide open discussion** on solutions, Blue readouts
14:30–15:15:	**Prioritization/convergence**
15:15–15:30:	Coffee break
15:30–16:15:	Blue readout, Red readout
16:15–17:45:	**Detailed planning**, Blue readout
17:45–18:00:	Feedback on process, planning for Sunday
18:00:	Dinner on Campus

Sunday Workshop: Morning Location Stanford Design School, Afternoon Location Stanford Geocorner/Braun Corner

9:00–09:30:	Coffee, Pastries & Fruit
9:30–10:00:	Recap of Saturday for Sunday-only participants (if any)
10:00–11:30:	Continue on detailed planning, use proposal outline
11:30–12:00:	Final Technical group readout (eg, 3+ selected ideas)
12:00–13:00:	lunch @ Geocorner/Braun Corner
13:00–13:30:	Read out Political/regulatory/social/funding groups [Online]

13:30–14:00:	Blue Report out summary [Online]
14:00–14:30:	Red Report out summary [Online]
14:30–14:45:	Vision for the future and next steps [Online]
14:45:	Closing remarks, picture in Quad and campus tour option
15:00 and later:	for organizers to collect workshop data and plan next steps

General workshop flow:

1. Collect as many ideas and voices as possible
2. Rate and consolidate
3. Prioritize (Likelihood vs. Consequences)
4. Add more details

Guiding questions:

5. Might this concept have a large impact if it works?
6. What is the data needed to be collected to see if it works?
7. What kind of modeling is required to test whether this will work?
8. What's the worst that can happen?
9. If something bad happens, is it reversible?
10. What are the concerns that need to be mitigated?
11. Is this topic worth continuing to pursue? What would we have to know to decide if this is a good idea to continue to pursue?
12. More questions?

Summary report out and Next steps:

- Facilitators/champions report out next steps and what could be accomplished/outcomes
- Red Team reports out key data that needs to be collected and key areas of concern

- Other report outs might include:
  - Financial
  - Political/regulatory/Public Policy
  - Social/Communication
- Final proposal(s) as output from workshop, ~2-3 months after event
  - Who, what, when, where, how much, next steps for gathering data and doing experiments and analysis
  - Schedule working follow up meetings

Subgroups:

- Modeling
- Field data/sensors
  - Aerogeophysics
  - Surface geophysics
  - Borehole-based glaciology
- Lab work, prototypes, Engineering, Logistics
- Strategic/vision, Political/Regulatory, Financial, Social

Scientific and Social Engagement process:

Questions to ask at each phase, ICE Cycle

- **Impact**: Who is going to be Impacted?
- **Contribution**: Who can significantly contribute to the process?
- **Engagement**: How to engage key stakeholders throughout the process? Who can we bring to the table?
- Repeat the cycle as new information comes into focus

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6 Attendance of the Stanford Workshop does not imply support of concepts expressed in this white paper, which is authored only by those listed on the Author page. In fact, Red Teams were invited and several participants attended the workshop to raise concern.

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Workshop Organization

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ADA Compliance

This document has been created to meet the standards of the Americans with Disabilities Act (ADA) of the US.