Report on the 2023 Future of Greenland ice Sheet Science (FOGSS) Workshop: Unifying Themes, Cross-Cutting Priorities, and Future Directions

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Executive Summary

The Future of Greenland ice Sheet Science (FOGSS) 2023 workshop was a hybrid meeting held March 22-24, 2023, at the Georgia Tech Institute for Technology with over 70 in-person participants and up to 150 online participants from across the U.S. scientific community studying the Greenland Ice Sheet (GrIS). Through a series of presentations and breakout groups, two unifying themes were identified: 1. U.S.-based scientists studying the GrIS must better engage with Greenlanders and their research needs; and 2. Open science will accelerate GrIS research, but data repository consolidation is needed. Previously identified major cross-cutting challenges in GrIS research were refined, including tighter integration of observations and models, quantification of meltwater fluxes, and ice-sheet modeling that is more responsive to the needs of Greenland communities. This research community is growing but needs to better synthesize progress in meeting community goals, and to reach consensus on its next major initiatives to clarify the future of the GrIS.

Introduction

The Future of Greenland ice Sheet Science (FOGSS) workshop was initiated in 2022 at the request of NASA and NSF program officers. FOGSS provides a forum for community engagement on the state of U.S. scientific study of the Greenland Ice Sheet (GrIS; *Sermersuaq* in Greenlandic) and to guide medium-to-long-term research priorities for U.S. research involving the GrIS. FOGSS also aims to increase the impact of current individual research projects by sharing best practices, strategizing about community opportunities and available logistics, and identifying the challenges that – if overcome – can accelerate GrIS research throughout interested communities.

Due to challenges associated with the COVID-19 pandemic, the first FOGSS workshop was held online on April 6-8, 2022, during three 3-hour interactive sessions. A summary slide deck of this workshop's key outcomes was generated that identified five key challenges for GrIS science (Chu et al., 2022). Because of the format and schedule constraints, that 2022 report was generated by the five organizers without further external input.

The 2023 FOGSS workshop was held March 22-24 in Atlanta, Georgia, on the campus of the Georgia Institute of Technology. The workshop had a hybrid format, with 70 participants attending in person and up to 150 online participants; there were 180 online registrants in total. This workshop report was produced using participant-generated notes preserved online during the workshop's interactive breakout sessions. It was drafted by the organizing committee then opened for public comment for two weeks. Seven individuals provided feedback on the draft, which the organizing committee incorporated here. Our goal is to synthesize workshop discussions and products, rather than provide an all-inclusive list of desired research and community efforts. This document is aimed at U.S. research agencies, primarily NSF and NASA, but is also relevant to several other agencies' research priorities (NOAA, DoE, DoD), in accordance with the workshop mission. The five cross-cutting themes proposed in 2022 were revised in 2023 accordingly:

Table 1. Original and Revised FOGSS community challenges

#	Original 2022 Challenges	Revised 2023 Challenges
1	Decolonizing U.S. research in Greenland	Equitable and inclusive U.S. research in Greenland
2	Better integration of observations and models	Better integration of observations and models, and observationalists and modelers
3	Water remains a unifying unknown	Quantify Greenland's water budget in a changing climate
4	Sustained, open polar observations	Sustained, open and FAIR polar observations
5	Projecting Greenland's contribution to sea-level rise	Projecting the Greenland Ice Sheet's impact on society

Unifying Challenges

All five of the cross-cutting challenges identified in 2022 were preserved in revised form in 2023 (Table 1). However, two were highlighted so frequently by 2023 workshop participants that they are highlighted first here as unifying challenges for the FOGSS community. They are linked thematically to the other three via their expression of the need for cultural and technical evolution in how our community does science.

- *Equitable and inclusive U.S. research in Greenland (Challenge #1)*

There was widespread enthusiasm among FOGSS participants to better connect studies of the GrIS and its periphery to the interests and needs of Greenlanders themselves, and also to better involve Greenlanders in U.S. research than has happened over the past century. The government of Greenland (*Naalakkersuisut* in Greenlandic) recently released its first national research strategy for the rest of this decade (Ministry for Education, Culture, Sports and Church, 2023). Of key relevance to U.S. researchers studying Greenland is the strategy's goal of better anchoring research in Greenland (*Kalaallit Nunaat* in Greenlandic) to Greenland and its inhabitants. This theme connects both evolving cultural priorities within the U.S. scientific enterprise (moving from "parachute science" to equitable and inclusive co-production), agency initiatives (e.g., NSF's Navigating the New Arctic program), and – most importantly – the desires of Greenlanders themselves.

A near-term community goal (by 2024) is that *all* research on Greenland is identified and registered in central hubs (Arctic Hub Connect and Isaaffik; Figure 1). Longer-term priorities include directly connecting international and Greenlandic researchers and students (e.g., Arctic Hub, JSEP), making all Greenland-relevant data FAIR (Findable, Accessible, Interoperable and Reusable; discussed further below), increasing incorporation of indigenous and local knowledge, and prioritizing the marine science that is important to both local fisheries and the future of the GrIS (e.g., ocean and fjord physical and chemical properties). Those FOGSS participants who have already engaged with Greenlandic communities and its government as part of their research identified the capacity of interested parties (e.g., time, financial) as a primary limiting factor in increasing engagement. This challenge was also acknowledged by Greenland's National Research Strategy. Language barriers remain a challenge, but translators exist and can overcome this barrier. The FOGSS community recognizes that capacity building for further U.S.–Greenlandic cooperation is a long-term effort but is central to the future of GrIS science.

While envisioning future research projects

- ☐ Read Greenland's National Research Strategy

- ☐ Review Arctic Hub's How-To Guide's for Research in Greenland

- ☐ Familiarize yourself with current research in Greenland via Isaaffik

While launching a research project

- ☐ Follow the How to Get Started Guide of Arctic Hub

- ☐ Share your plans and identify local synergies, via Arctic Hub

- ☐ Register your project with Isaaffik

- ☐ For projects with fieldwork, apply for appropriate permits

During and at the conclusion of your project

- ☐ Share your findings with local stakeholders

- ☐ Share your findings through Arctic Hub

- ☐ Create metadata records on Isaaffik to published papers and FAIR data

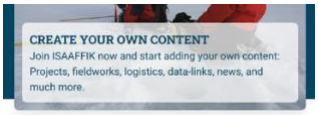

Figure 1: A recommended workflow, with action items, for how best to support and engage with Greenland research, using Greenland-supported guidance and tools. Each action item and website snippet links to documents, representative instructions, or help pages.

- *This is the way: Sustained, open and FAIR polar observations (Challenge #4)*

Open data and code sustain our community and should be a program imperative. As datasets continue to grow rapidly, a major challenge facing the scientific community is efficient access and use of data and code. This challenge is broadly felt across the U.S. government and led to 2023 being declared the Year of Open Science. We consider "efficient" use to be when scientists that are not involved in their collection or development can readily identify such products as meeting their needs and leverage them to develop new scientific understanding. Efficient data and code use is acknowledged by our community as a major accelerant of our science. From a programmatic perspective, efficient data use maximizes the return on investment from expensive field- or satellite-based data collection; the consensus expectation is that the cost needed to make

data and code FAIR is significantly lower than the cost needed to produce potentially duplicate resources.

Open science was identified as a significant unifying theme for many of the cross-cutting challenges proposed following the 2022 workshop and refined during the 2023 workshop. Equitable and inclusive U.S. research in Greenland (Challenge #1) requires that research conducted in and about Greenland be accessible to Greenlanders. Data–model integration (Challenge #2) is improved when data and model output are both at the fingertips of the scientific community, with all necessary corrections and caveats clearly documented. The cross-cutting challenge on sustained, open polar observations specifically identifies this theme (Challenge #4). Open science also empowers the remaining two challenges (#3 and #5).

Resources and initiatives that support open science are expanding, and these efforts should continue to be promoted/mandated by program officers. Computational resources are a critical component of open data and open code, but human resources are also essential. Training and skill building in these areas can unite observationalists and modelers and are likely to build understanding through transdisciplinary collaboration. More opportunities are necessary, but FOGSS 2023 partly addressed the training need through an optional third day of software tutorials, but more such opportunities are needed. Open science is best achieved using approaches beyond data sharing (e.g., through a DAAC); now, tools such as MyBinder and Jupyter Notebooks allow data and code to be run without prior expertise, dramatically reducing barriers to building on existing science (e.g., CryoCloud; Snow et al., 2023). These software tools allow entire workflows and analyses to be reconstructed with minimal effort (e.g., Mankoff and Tulaczyk, 2017; Bach et al., 2018; Mankoff et al., 2021; Black and Joughin, 2023; Figure 2).

Our community recognized one potential threat to open and FAIR polar observations emerging through the very efforts to achieve them. While the recent proliferation of open data and code resources available to GrIS-interested scientists are powerful and compelling steps in the right direction, we also note that this expansion of opportunities challenges our community as researchers run the risk of not knowing *which* repositories to search (e.g., GHub; Sperhac et al., 2020). We anticipate that future consolidation will further increase efficiency of GrIS study. We share one view of the software ecosystem in the figure below, as a resource for the FOGSS community.

Finally, *sustained* observations are also critical to transform Greenland Ice Sheet Science, along with open science and FAIR principles. While space-based optical, laser altimetry, velocimetry, and gravimetry are important observational strengths, the dearth of long-term, in-situ observations are a significant limitation to ice sheet understanding. Ongoing, in-situ observations on the ice sheet are now largely restricted to those of the Danish PROMICE network and the U.S. Summit station. We are unaware of any long-term monitoring of subsurface ocean conditions near outlet glacier termini, where warm water is widely expected to have a strong influence on ice sheet mass loss.

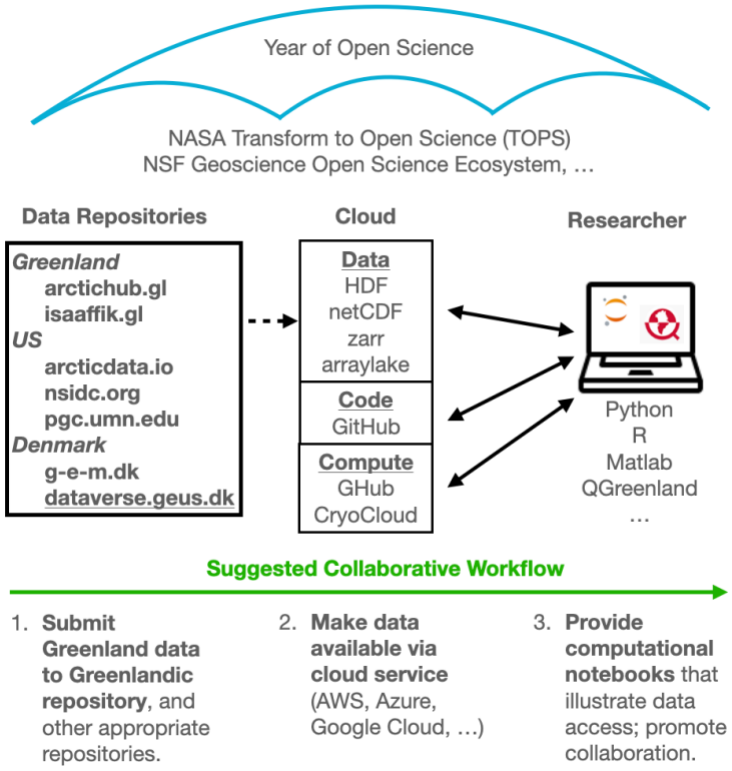

Figure 2: An integrated workflow for collaborative Greenland research, including Greenland-specific data repositories, widely used cloud computing environments, and Greenland-specific portals.

Cross-Cutting Challenges

The 2023 workshop included keynote presentations and several hours of breakout group discussions for participants to discuss the challenges named in the 2022 workshop report. Breakout groups were invited to reframe each challenge as they saw fit (see Table 1), and identify the near and long-term priorities necessary to make progress on each challenge. Additionally, workshop participants were invited to propose new challenges although most concerns fell within one of the existing challenges. Participants identified Challenges #1 and #4 as "unifying" (see above). Here we summarize several short-and long-term initiatives proposed by breakout groups focused on Challenges 2, 3, and 5.

- *Challenge #2: Better integration of observations and models, and observationalists and modelers*

At present, GrIS research is typically siloed into focused studies that either observe new ice-sheet processes and better understand their function, or studies that model these processes or changes. Participants agreed that funding agencies should prioritize studies that tightly integrate both approaches, but without overburdening the relatively fewer ice-sheet modelers in our

community. Such prioritization could come through mandates (e.g., specific funding solicitations) or extra credit during proposal review (e.g., some specific performance metric during review). Specific training for all new glaciological researchers that includes the practice of modeling and the practice of observational methods would also be valuable in training new researchers conversant in both dominant research paradigms. Such efforts will be further supported by the push towards open data and open computing described in the Open Science Unifying Theme.

- *Challenge #3: Quantify fluxes of Greenland's water budget in a changing climate*

As Arctic summer becomes hotter and longer, surface meltwater flux is a growing component of GrIS mass balance (e.g., Mankoff et al., 2021; Lenaerts et al., 2019). This year, FOGSS participants boiled down the 2022's #3 challenge ("Water is a unifying unknown") to a more fundamental problem: The budget of the GrIS remains unclosed, as the underlying surface, englacial and subglacial hydrological processes are poorly quantified. Our current inability to characterize the spatial and temporal variations of glacial hydrologic processes remains a great challenge. Furthermore, poor understanding of glacier hydrology links to mass loss at outlet glaciers, where subglacial discharge mixes with warm ocean water to melt termini. The next notable challenge is that these processes are often studied by numerous different research communities, including many working in atmosphere sciences, terrestrial hydrology, geomorphology, and paleoclimate. This creates additional challenges to keep track of the latest research progresses and new hypotheses related to GrIS's water budget. Several near-term tasks have been proposed to tackle this problem, including the establishment of a unified Greenland hydrology working group. This working group would conduct regular workshops to integrate the multiple disciplines studying Greenland's meltwater. Through these channels, the hydrology community can then: 1. Assess the current state of understanding of the processes that govern GrIS water fluxes; 2. Identify high-priority study areas that address leading uncertainties in closing the water budget. This workshop would integrate both disciplines that have historically investigated the GrIS (e.g., glaciology, hydrology, geophysics, fjord oceanography) and those disciplines with typically subpolar regions of interest (e.g., surface and subsurface hydrology, open-ocean oceanography), with the goal of closing the GrIS water budget and quantifying hydrologic impacts on submarine ice melt. Such efforts will improve ice-sheet and biogeochemical modeling for the benefit of local and global communities.

- *Challenge #5: Projecting the Greenland Ice Sheet's impact on society*

FOGSS participants universally recognized the importance of community based future mass-balance projections, i.e., the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6). However, FOGSS participants additionally identified opportunities to ensure that model development and projections are better targeted at supporting the needs of diverse communities. Such a workflow could begin with identifying key community needs, including but not limited to projected mass change, such as terminus retreat or iceberg discharge near specific Greenlandic communities. Following that, projecting the impact of the GrIS on society would be enhanced

through identifying the needs of models to meet these community needs, such as improved process understanding or better assessment of historical climate forcings. Finally, these model needs would drive prioritized observational and modeling studies. Findings would then be communicated back to the communities to identify new community-led priorities. Such a tight linkage is recognized as the ideal but is not yet achieved.

Future Directions

- *Measuring progress on FOGSS priorities*

To measure long-term community progress on FOGSS research priorities, and to determine if new priorities emerge, the FOGSS Organizing Committee will prepare a questionnaire that will be sent to participants in advance of the next 2024 workshop. Questions will focus on the past year's achievements, such as assembling a list of activities related to those goals, recent studies, and on challenges related to diversity, culture, inclusion, and training. Some examples are listed below:

→ Are we making progress in our understanding of Greenland Ice Sheet change?
→ To what extent does _____ remain a cross-cutting challenge for our community's understanding of the Greenland Ice Sheet?
→ What challenges exist that we have not yet acknowledged or begun to meaningfully address?
→ How confident are you in our understanding of GrIS mass balance and the processes that control it?

- *The next big thing: Possible themes for FOGSS 2024*

The GrIS has been a focus of U.S. scientific research since the 1950s, but it is vast and variable, and our understanding of its past, present and future has benefited greatly from larger-scale research programs – from Camp Century to GISP2, PARCA to Operation IceBridge, and several others. However, with the conclusion in 2021 of both of NASA's Operation IceBridge and Oceans Melting Greenland missions, U.S.-led study of the GrIS appears to have recently passed an inflection point in the undertaking of new, large-scale investigations. The study of the polar cryosphere from space is undoubtedly in the midst of a golden era (e.g., NASA's ICESat-2, GRACE/-FO and upcoming NISAR collaboration with ISRO; ESA's CryoSat-2 and Sentinel-1/2/3 constellation). However, measurements and process-based studies that are only possible through ground-based, shipborne and airborne campaigns are not occurring at the same rate and scale as has occurred during the previous decade.

Given the current situation, FOGSS participants recognized and prioritized the outsized scientific potential of larger-scale programs and missions that take a more holistic assessment of mechanisms of ice-sheet change compared to what is possible through smaller projects. This was demonstrated by the interest in "super-sites". An Antarctic example is the U.S./U.K. collaborative

International Thwaites Glacier Consortium. In Greenland, the ongoing foundation-funded Helheim Glacier project or the NSF GreenDrill project are smaller-scale examples. FOGSS 2024 should seek consensus on what the next major programs or missions to study the GrIS ought to focus on scientifically, and how they could be realized technically and programmatically. FOGSS 2024 should also consider the recapitalization of Summit Station and the possibility of using it as a research hub.

Arguably comparable to a “super-site” in terms of effort, funding and societal imperative is securing a stable future for development of GrIS mass-balance projections. Many participants identified the community-based projection syntheses like ISMIP6 as critically important. However, there is no simple mechanism to fund all U.S.-based ISMIP participants, let alone its large network of international contributors. A new funding model, or perhaps an explicit expectation that modelers include ISMIP participation within future proposals, would support this effort. If desired, the FOGSS community could provide input on future ISMIP experiment design and deliverables.

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