EarthCube Data Capabilities:
QGreenland: Enabling Science through GIS

- QGreenland will be an **open data, open platform tool** to improve geoscience and interdisciplinary Greenland-focused research, data discovery, learning, decision making, and collaboration.
- QGreenland will combine key disciplinary and interdisciplinary geospatial datasets into a **unified, all-in-one GIS analysis and visualization environment for offline and online use**.
- An **international Editorial Board and Project Collaborators** will connect the QGreenland Team to data and user communities in Greenland and across the globe, and advise development to optimize community use.

1. MOTIVATION & SCIENTIFIC RATIONALE

1.1 Interdisciplinary Data & Analysis Needs

Greenland is the largest island in the world, draped with an ice sheet and home to over 56,000 people. Straddling the north Atlantic, North America and the Arctic, Greenland is a unique region with global impact; its ice sheet holds enough water to raise global sea level by about 6 meters and its melt is accelerating (Bevis et al., 2019), it hosts potentially valuable deposits of oil and gas (Boersma & Foley, 2016), metals (Thrane 2018), and even sand (Bendixen et al., 2019), and its land and waters feature rich local and migratory biodiversity (CAFF, 2013). As researchers, stakeholders, local residents, and learners across the globe continue to study, manage, explore, and inhabit Greenland, more **integrated geoscience and cross-discipline knowledge is necessary** to understand the complex and connected processes acting in Greenland and influencing its development and global role in years to come.

Greenland-focused knowledge crosses disciplinary boundaries, from glaciology to geology, social sciences to ecology. The community has substantial data resources, but data is scattered across sources, in many formats, and selecting the right datasets requires specific expertise. The **effort and expertise needed to find and integrate data is a substantial barrier to use**. GIS (Geographical Information System) platforms can also be intimidating to new users, creating an additional barrier to wider use of important geospatial data.

Researchers, educators, decision makers, and communities want to use geospatial data, but there is no ready-to-use interdisciplinary platform for combining spatial data. Such a platform would:

- Provide interdisciplinary data in an integrated environment;
- Reduce startup time for all user groups, and allow online and offline use;
- Increase data use, and develop a connected user group;
- Take advantage of high quality open-source software;
- Provide a shared platform and data structure, with functionality from basic data viewing to advanced visualization and analysis; and
- Support interdisciplinary data exploration for science, education, and decision making.

1.2 Why QGreenland

Some online GIS platforms and GIS data servers exist. These data platforms and services, however, fall short of meeting broader user needs.

First, there are several online, disciplinary GIS platforms that serve Greenland-focused users: the Pikialasorsuaq Atlas provides data layers pertaining to the Pikialasorsuaq (the North Water Polynya) that focus on indigenous and scientific knowledge mostly on wildlife, people, and management; the

Government of Greenland NunaGIS platform has a similar focus on wildlife, culture, and management; the Government of Greenland Minerals and Petroleum license map; and the Danish Center for Environment and Energy, University of Aarhus online GIS platform on important areas for wildlife. While all useful, these platforms have several drawbacks because they:

- Are highly disciplinary, including that they provide little or no Earth and geoscience data;
- Have data which are selected by the hosting organizations rather that driven by user communities;
- Are hosted on platforms with limited functionality for analysis and visualization;
- Include limited or no ability to download data as individual or group layers; and
- Require online access.

For those in the field or working in Arctic areas with low-speed Internet, online platforms can require prohibitive levels of bandwidth; this is particularly relevant to those living on and working in Greenland but can also cause problems for outside users if the data is hosted in Greenland. Even something as seemingly insignificant as a user's browser preference being incompatible with web-based platforms can restrict data access to these online platforms.

Second, there are various data portals containing and serving Greenland geospatial data. These include the NSF Arctic Data Center (NSF ADC), the National Snow and Ice Data Center (NSIDC), and

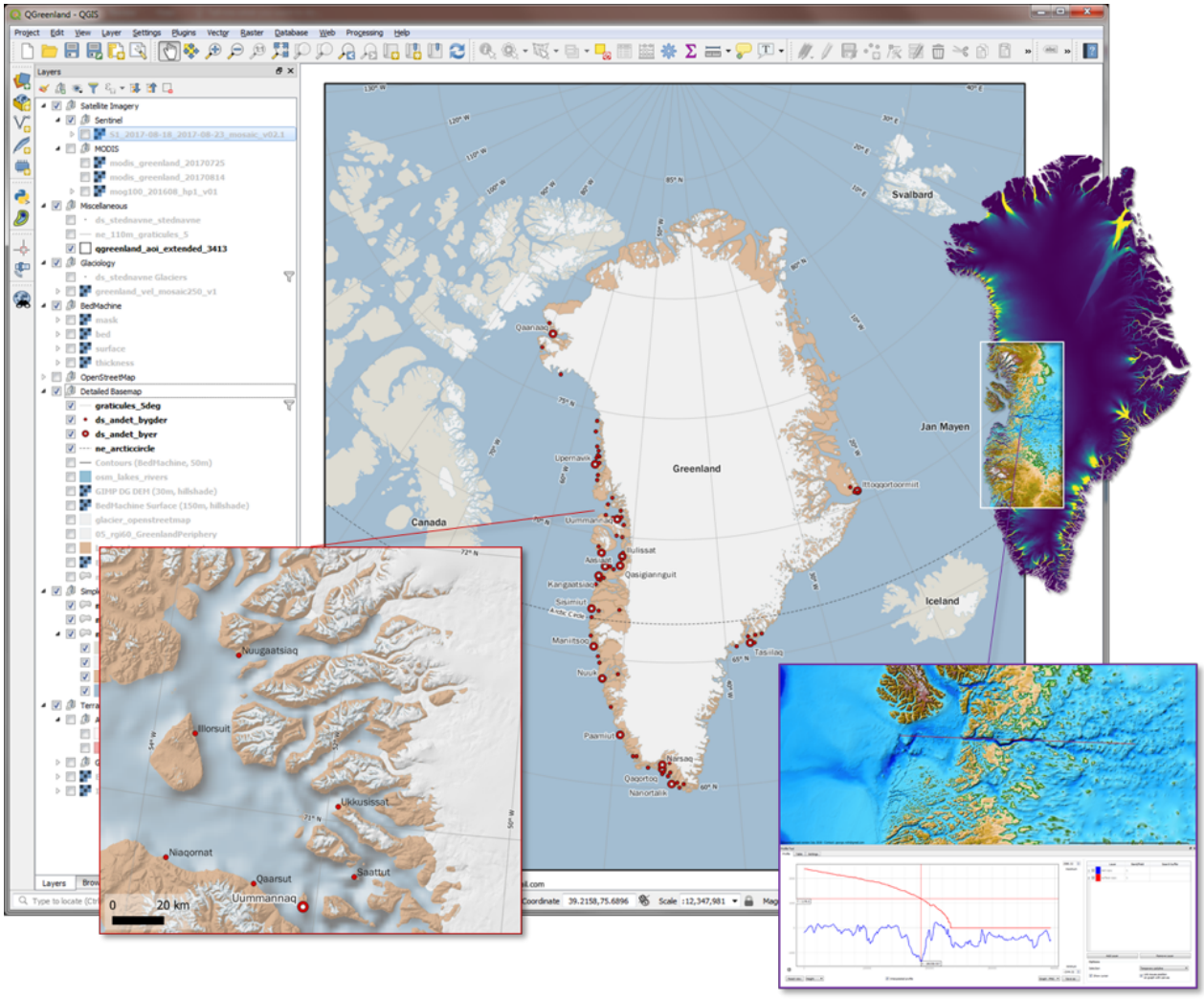

Figure 1. Visualization of QGreenland GIS environment. Highlighted features include a basemap, interdisciplinary data investigation, easy dataset visualization, ad dataset interrogation.

the Arctic Spatial Data Infrastructure (Arctic SDI). However, there is no unified environment for analyzing and visualizing full-quality data across many scientific disciplines. Presently, researchers must search for, download, import, and style individual basemap and scientific datasets. This process can be slow and difficult, costing time and resources, and result in a massive duplication of effort across the Greenland research community.

Third, with disciplinary data housed at different archives and limited ability for individual researchers to identify key datasets outside of their expertise, exploring cross-discipline research is also rarely feasible. Educators, who may have even less experience with Greenland data, are left to navigate a data system designed for researchers, and are unlikely to have the time to invest in developing a Greenland GIS environment for teaching.

Our project, called QGreenland, will address the limitations of both the current online GIS platforms and data services by providing an interdisciplinary, consistent, and comprehensive package of pre-imported, pre-styled data that is immediately ready-to-use online or offline (Figure 1). QGreenland is modelled off of the widely used, award-winning Quantarctica package, developed by Project Collaborators at the Norwegian Polar Institute, which provides a geoscience-focused GIS package for Antarctica. QGreenland Project Consultant and Quantartica developer George Roth received many user requests for a QGreenland tool and actively sought out project partners to make this package a reality; all interested groups are included as Project Collaborators for this proposal. Further, we envision QGreenland as a stepping stone to a full Q-Arctic environment, fostering accelerated interdisciplinary research, decision making, and learning across the Arctic.

1.3 Objective

Using QGIS, a free, open-source, cross-platform GIS environment as the foundational software environment, QGreenland will offer a freely-redistributable, offline-capable package of original-quality data and software that will:

- Provide up-to-date, free and open scientific data, including metadata and citation information;
- Include consistent, professionally-styled, overview data that works across spatial scales;
- Provide production-quality map and figure design tools; and
- Enable and support rapid, community-driven data discovery and research analysis.

2. REALIZING QGREENLAND

QGreenland will be a complete GIS tool developed through diverse, international user and expert input, implemented by mapping and data experts, with further support from communication and training specialists. The project will be overseen by a skilled QGreenland Team, an Editorial Board will help ensure the quality and utility of the data is included, and Project Collaborators will provide connections to datasets and user communities.

2.1 QGreenland Organization & Project Collaborators

The QGreenland organizational structure (Figure 2) includes the QGreenland Team (section 5.3), multiple user communities (section 2.4), Project Collaborators, and an interdisciplinary Editorial Board. Based on Quantarctica team experience, and following the successful model ultimately created for Quantarctica, a key organizational component of QGreenland will be an international, interdisciplinary Editorial Board whose members are community leads, some of whom will represent Project Collaborators. The role of the Editorial Board members is to: help identify, evaluate, and select community datasets that are valuable for the entire Greenland community and for individual disciplines; communicate their community and collaborator needs and requests to the QGreenland Team; promote QGreenland use within their disciplines and communities; and connect other individuals directly to the QGreenland Team when appropriate. The Editorial Board will be formed within the first six months of the project. Editorial Board members will meet online quarterly and be asked to be responsive to individual inquiries (1-2 per month). Term lengths for each Editorial Board member will be determined at the onset, with a potential to turn

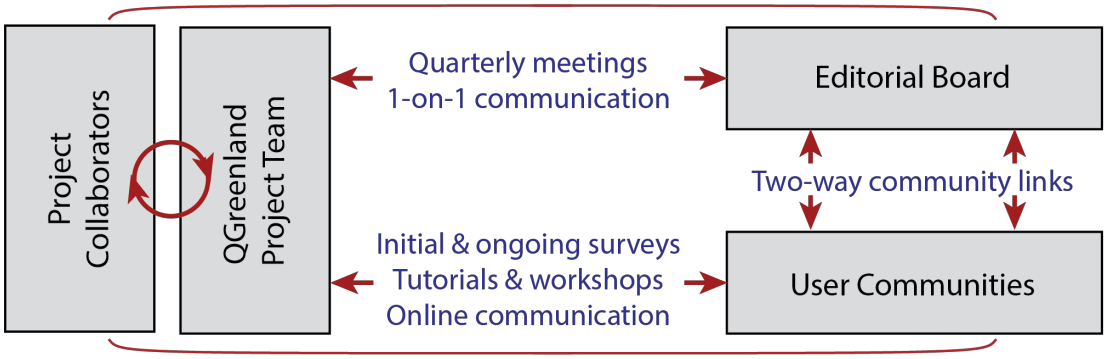

Figure 2. QGreenland organizational chart showing modes of interaction among the QGreenland Team, Editorial Board, Project Collaborators, and user communities.

over each Board seat once during the grant period. This allows multiple voices to represent each Board theme (Table 1) and provides an agreed upon schedule for Board and QGreenland Team members to evaluate the relationship effectiveness. We will seek Board members with some geospatial experience, an interest in cross-disciplinary interaction, and developed expertise within their theme. We will also endeavor to create an Editorial Board with representation across genders, underrepresented groups, and diverse locations.

Editorial Board Theme Areas		
Glaciology	Atmospheric Science	Indigenous Knowledge
Geophysics	Oceanography	Built Environment
Geology & Natural Resources	Ecology	Human Health
Paleo-data	Biology	Social Science
Sea Ice	Hydrology	Political Science

Table 1. Editorial Board member theme areas. Note that theme areas are not exclusive, and data from other areas can be included.

The Editorial Board spans a wide range of disciplines (Table 1) and our diverse set of Project Collaborators will help identify Editorial Board members and connect the Team with valuable datasets and user communities. An international group of Project Collaborators will support these activities, as discussed in Table 2.

2.3. QGreenland Data

The QGreenland package will be available for download from the QGreenland website, served by NSIDC. It will be provided as a full standard package, and data layers will also be available for individual download directly or via links to established data archives. The full QGreenland package and data layers will also be available via download mirrors hosted at other institutions. For example, Quantartica is served from mirrors in Norway, Australia, India, Japan, and the United States. We expect that some of the institutions hosting Quantarctica will also be interested in hosting QGreenland, and we will seek additional partners as needed to ensure QGreenland availability and timely downloads globally.

As an EarthCube data project, QGreenland project principles include using and creating Findable, Accessible, Interoperable, and Reusable (FAIR) data guidelines. The data access and management standards discussed here are responsive to FAIR principles, and FAIR principles will guide any additional data questions that arise after project start. Our goal is to optimize use of FAIR standards while allowing

Project Collaborators (Organization & Contact)	**Collaboration Notes**
Geological Survey of Denmark and Greenland (GEUS) Signe Bech Anderson, Niels Korsgaard, and Nanna Karlson	GEUS collaborators have been active in pursuing QGreenland development, and will contribute and support data sharing and integration, for example for Programme for Monitoring of the Greenland Ice Sheet (PROMICE) data and hosting user workshops as needed.
Technical University of Denmark (DTU) René Forsberg	Forsberg has been active in encouraging QGreenland development, and DTU is ready to bundle data for QGreenland: e.g., from the European Space Agency Climate Change Initiative, coastlines, digital elevation model, and geoid model data.
Danish Meteorological Institute (DMI) Ruth Mottram	DMI is a primary Greenland data developer and provider. DMI is also a Polar Portal partner and will provide cross-connections/cross-promotion with Polar Portal partners.
Norwegian Polar Institute (NPI) Nalân Koç and Kenny Matsuoka	NPI developed the successful Quantarctica package that QGreenland is based on, with Kenny Matsuoka as lead PI. NPI will provide occasional consulting regarding experience and expertise gained while creating Quantarctica.
Arctic Data Committee (ADC) Peter Pulsifer	The IASC-SAON (Sustaining Arctic Observing Networks) ADC will form a working group to collaborate with QGreenland to identify and mobilize relevant data from across disciplines. ADC's purpose is "*to promote and facilitate international collaboration towards…access to Arctic data through useful, usable, and interoperable systems*", and their links to major Arctic data centers in all Arctic nations will provide excellent breadth and wide resources to support QGreenland.
International Arctic Science Committee (IASC) Larry Hinzman	IASC collaboration will focus on user community connection and development. A QGreenland Training Workshop will be held at IASC's Arctic Science Summit Week. IASC may be able to fund additional science activities.
World Wild Fund for Nature Denmark (WWF-Denmark) Mette Frost	As an international non-governmental organization, WWF-Denmark has key connections with Greenland stakeholders and organzations outside of academic research. WWF-Denmark will provide input on useful stakeholder data and connections within this community.
U.S. Polar Geospatial Center (PGC) Paul Morin	As producers of the Arctic Digital Elevation Model and a central U.S. resource for geospatial data, PGC will collaborate on data, and also be a useful initial user group for geosciences.
Greenland Ice Sheet Ocean Science Network (GRISO) Fiamma Straneo	GRISO, an EarthCube-funded activitiy, will collaborate on data and connect QGreenland to the ice sheet and ocean research communities.
Polar Computing RCN Shantenu Jha	We will collaborate with the EarthCube High Performance Distributed Computing (HPDC) in Polar Sciences RCN to consult on their RCN findings, assist in data identification, and link to additional user communities

Table 2. Formal Project Collaborators, contacts, and contributions. All Collaborators may support Editorial Board functions. See Letters of Collaboration for confirmation of coordination.

for fully offline functionality for the standard data package. QGreenland will provide data across three categories:

- *Category 1*: Valuable for the full user community and appropriate for offline functionality. Category 1 data will be included in the QGreenland standard base package.
- *Category 2*: Discipline-specific and approprate for fully offline functionality. Category 2 data will be available for individual download via the QGreenland website.
- *Category 3*: Disciplinary and community-wide interest datasets that are large enough that they require online access to optimize use. Based on community-wide or disciplinary interest, Category 3 data layers will be included as online-only access layers in the standard QGreenland package (they simply do not work when offline) or as suggested add-ons.

Dataset identification will be a key collaborative activity among the QGreenland Team, Editorial Board, and Project Collaborators. For example, the Arctic Data Committee (ADC) and its partners are working to create a matrix documenting over 70 polar data catalogues that hold 1,000s of datasets. The ADC is working on a federated database system that will enable a single window search of these data via Google, and the ADC expects that this tool will be available by the QGreenland project start. Tools like this will support identification of diverse datasets. Similarly, Project Collaborators developing online platforms and disciplinary GIS data, such as DMI, GEUS, and DTU, will help to identify the most up to date GIS data and identify valuable disciplinary and interdisciplinary data layers.

Key to making the Google Dataset Search Tool facilitate FAIR data are open and collaborative vocabularies and metadata structures. Maintaining and creating complete and consistent metadata will likewise be key to ensuring that QGreenland data is findable and citable. All data will be archived at the NSF ADC, which is working to make all holdings searchable via Google Dataset Search. They also work closely with EarthCube Project 418 (P418), and will be publishing JSON-LD metadata for all holdings, which will be compatible with the Schema.org initiative and P418. NSF ADC is also a DataONE member repository, so all QGreenland data will be searchable via DataONE. We will also submit metadata to the EarthCube Data Discovery Studio.

QGreenland will use a combination of original and restructured datasets. All data that QGreenland provides will have an open access type license allowing full, free redistribution and no restrictions, following explicit permission from the original data authors. In some cases, data identified to include in QGreenland will already be appropriately formatted for inclusion. In this case, the data layer will be provided with the full original metadata and QGreenland will duplicate and link to the original archived data. In other cases, data will need to be modified for QGreenland; for example, resampling, reprojection, interpolation, or style modification. All modified datasets will be fully archived at the NSF ADC, including assignment of individual DOIs. All original metadata and full citation data will be maintained, along will additional metadata documenting all modifications. For all QGreenland data, modified and unmodified, full original citation information will be provided, and all users will be requested to use the original data citations for publishing QGreenland-produced maps and figures.

All QGreenland data layers will be formatted into easily reusable vector and raster files with consistent projection and full layer definition (including layer metadata, labels, and styling). Vector files will be formatted as ESRI Shapefiles (and/or other comparable commonly-used vector format) and can include point, line, and polygon data. Raster data will be formatted as GeoTIFF files (see Data Management Plan for additional details). Formatting standards will also be published on the QGreenland website, including tutorial instructions, to facilitate users in 1) formatting their own data for import into QGreenland for individual projects and 2) creating data layers that can be shared with the whole QGreenland user community. These instructions will include information on creating appropriate metadata, attribute tables, styling and labeling, compression, building raster data pyramids, and applying a QGreenland-consistent map projection.

2.3 The QGreenland Tool

The QGreenland package and software tool is based on the successful Quantarctica package, which has enhanced Antarctic focused research and education around the world. Like Quantarctica, QGreenland will be a GIS data package designed to work on the free, open-source, cross-platform GIS software QGIS. QGIS was first developed in 2003 and is one of the most widely used GIS systems globally.

Since QGreenland takes advantage of the QGIS platform, users can choose to work with QGreenland as a unified GIS research environment, or as a base environment for specific projects. Using QGIS functionality, there is full-range ability for users to import, analyze, and visualize their own data with the QGreenland data (Figure 3). Similarly, layers can be selectively copied or downloaded from QGreenland to use in other QGIS projects or in any other software supporting standard GIS formats.

QGreenland will support both offline and online use. The standard QGreenland package will be designed as a standalone download, with all Category 1 datasets fully downloaded onto the user's work machine. In this way, QGreenland is the perfect GIS tool for use in the field in Greenland, or in any location where online access is limited or nonexistent. For datasets that are valuable components of this standard package, but require too much disk space for offline use, we will downscale or similarly resample the data to be included in the QGreenland standard package as a reference data map. Additional online-only data layers will enable access to full resolution Category 1 and Category 2 data (disciplinary data) as well as Category 3 data (large datasets).

Instruction on the online/offline functionality of QGreenland and standards and methods for users to incorporate their own data with QGreenland will be provided through written, visual, and video tutorials on the QGreenland website (section 2.5).

Figure 3. Users can connect to optional Category 3 web layers (like the Bing Maps Aerial layer, left) for high-resolution data for local field planning and feature digitizing, or download daily satellite image (MODIS Terra, right) to enhance with included basemap layers and terrain rasters.

2.4 User Community Development

Developing the QGreenland user community is about creating cross-discipline and cross-community connections, enhancing the discovery and use of Greenland-focused geospatial data, and supporting the long-term sustainability of QGreenland tools and software. We seek to create a package, and the outreach and support materials needed, to serve users in scientific research, education, decision making, logistics, and community applications (Figure 4).

Learning from Quantarctica, QGreenland's development will begin with a broad user survey and incorporate user input throughout the QGreenland process. The initial survey will help to scope and prioritize the breadth of data to be included in the project and the numerous potential use cases. Questions will include: GIS data use, spatial and temporal bounds of interest, suggested datasets, use cases, knowledge and interest in data themes and connecting fields, knowledge and interest in training materials, and venues and events for in-person QGreenland Training Workshops. Follow-on surveys will occur at

the end of year 1 and the end of year 2, and will accompany workshop and QGreenland package dissemination activities (section 2.5). In addition to using institution and community listservs and social media, Quantarctica developers found that formation and cultivation of a Quantarctica email list was one of the most effective ways to distribute information on the package, updates, and news. We will develop a QGreenland mailing list, with special attention to attracting early career and underrepresented users. All users will find community and support via a shared interactive online QGreenland space. Building on the work of the US Interagency Arctic Research Policy Committee (IARPC), we expect this interactive online space to be an independently-formed team on the IARPC Collaborations web platform but other platforms (e.g., Slack, GitHub, etc.) will be considered, and the QGreenland website will provide a direct link or hosting services as needed.

Along with existing QGreenland Team connections, the QGreenland Editorial Board and Project Collaborators will play a key role in reaching potential user groups. We will ask Editorial Board members and Project Collaborators (Table 2), which include both national and international individuals and organizations, to provide two-way connections between QGreenland and their organizations and communities, and promote awareness and use of QGreenland. Many Editorial Board members and Project Collaborators will also be early QGreenland adopters. In this ongoing conversation, we expect input that will shape initial creation of QGreenland and inform improvements throughout development. Other early adopters will also help shape development. Immediate user groups we will target include scientific researchers, local Greenland communities, educators and communicators, and Arctic-focused organizations and projects.

In another aspect of learning from Quantarctica's success, while Quantarctica partnered closely with SCAR (the Scientific Committee on Antarctic Research), QGreenland will engage with SCAR's Arctic analogue, IASC (the International Arctic Science Committee). IASC facilitates international and interdisciplinary scientific cooperation, which directly aligns with the goals of QGreenland. IASC's broad working groups (Atmosphere, Cryosphere, Marine, Social & Human, and Terrestrial) and 23 member countries will provide data input, possible Editorial Board members, and QGreenland users. In addition, it is likely that IASC will be able to financially and logistically support the development of the QGreenland community through QGreenland Training Workshop opportunities, in particular aligned with the annual Arctic Science Summit Week. As IASC Executive Secretary, Co-PI Pope is well positioned to promote an interactive QGreenland – IASC relationship.

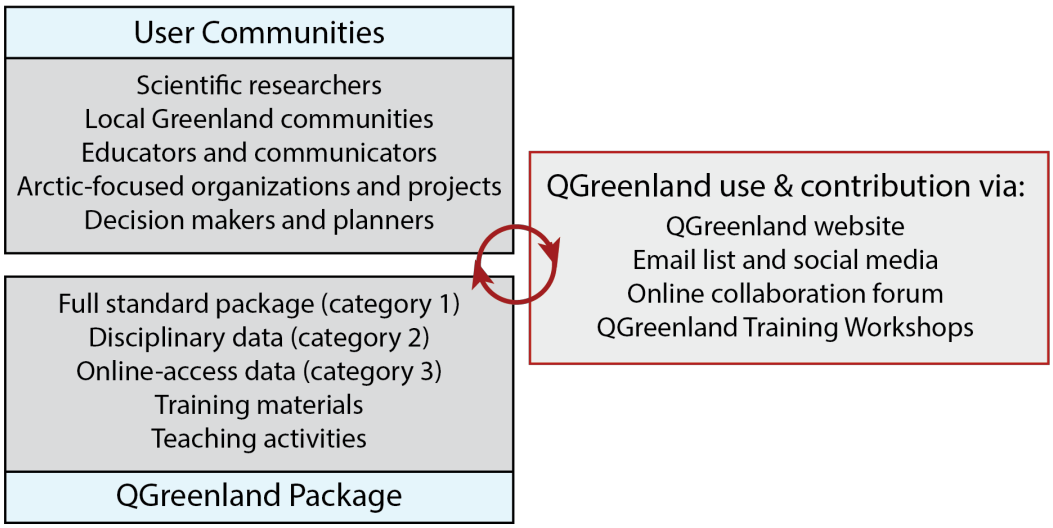

Figure 4. QGreenland products, QGreenland users, and modes of interaction.

Project Collaborators and Editorial Board members will also facilitate communication with developers and users of complimentary GIS projects, like the Government of Greenland and Danish Center for Environment and Energy. We expect that existing users of these online platforms will be interested in the QGreenland package, and that QGreenland users may want to use these online platforms for accessing data that is not part of the QGreenland package. The goal is to support connected use and awareness across tools.

2.5 Dissemination & Training

Getting QGreenland into the hands of users, and ensuring they know how to use and contribute to QGreenland (Figure 4), will aid user community development and ensure that QGreenland enhances scientific research, learning, and decision making.

Online resources will include written, visual, and video tutorials. These items will cover how to: set up QGIS to optimize use of QGreenland, work with the various QGreenland data layers, use offline and online datasets, format new data to add it to the QGreenland user environment, contribute new data for QGreenland community use, and join and contribute to QGreenland package tools. We expect online tutorial material to emphasize interaction with QGreenland, rather than focus on GIS and QGIS basic knowledge. We will, however, include links and resources for those who are new to GIS and QGIS to learn these foundational elements so that they can better interact with QGreenland. Tutorial material will be developed in response to user surveys, user feedback online and at in-person workshops and trainings, and based on specific use cases for target user community groups. We will also deliver 2-3 virtual QGreenland Training Workshops, which will be recorded and posted online.

The Quantarctica team found that in-person interaction was critical for maximizing the Quantarctica user base, encouraging further package dissemination, guiding product development, and creating an interactive community. In-person trainings are an emphasis of the QGreenland dissemination and training program. The Quantarctica team found that 3-hour training sessions with 2 instructors was optimal for sharing knowledge and getting users up to speed with hands-on interaction. We will mirror this training workshop design. QGreenland Training Workshops will be targeted for 25+ participants. Participants will be asked to bring their own laptops or, in some cases, we may provide training at a computer lab – in both instances the focus is ensuring that users complete the full installation process and become familiar with QGreenland datasets and GIS environment so that they can leave the training ready to use the QGreenland package for data inquiry and visualization.

Because QGreenland will be designed as an international community tool, training sessions are planned for the U.S. and other countries, including Greenland. We will primarily take advantage of existing conferences for providing add-on QGreenland Training Workshops. These will include Arctic-focused (Arctic Science Summit Week), geoscience focused (AGU & EGU) and system focused meetings. The Editorial Board and Project Collaborators will help to identify the best locations and community events for training, including in Greenland.

To take full advantage of conferences attendance, we will include a swath of activities at each meeting, with some content changes depending on project stage. Conference activities will include: an informational QGreenland poster and/or oral presentation, informational booth (may be combined with another group), user surveys and one-on-one QGreenland interactions (to explore user needs, provide hands-on assistance, and foster QGreenland package dissemination), in-person meetings with Editorial Board members and Project Collaborators as possible, and full QGreenland Training Workshops, with an aim to provide scientist and educator workshops whenever appropriate.

3. INTELLECTUAL MERIT & SCIENTIFIC OUTCOMES

QGreenland is designed to provide immediate impact for scientific research and exploration. QGreenland's strength is providing a flexible platform to allow the Greenland research and user communities to drive forward their own science. As a geoscience-based but interdisciplinary data

package, it will assist in cross-community system science. Arctic system science is increasingly recognized as a critical expansion of scientific research, supporting understanding of: extreme events; system feedbacks; tipping points; economic, social, and culture interactions with the physical environment; built environment and geoscience connections; and future projections for planning across environments. Assessing and accessing data across the Arctic system is, however, a challenge. QGreenland will break this barrier.

The proposed development of QGreenland is based directly on requests from the research community and needs identified by U.S. agencies. The EarthCube Polar Research Coordination Network (RCN) draft report on High-Performance and Distributed Computing (HPDC) for the polar science and data community discusses major barriers to improvement, including: "*Commercially Licensed Software: One of the big barriers to the uptake of HPDC … has been playing out, for example, with the replacement of ESRI's ArcGIS with the open-source QGIS in many geospatial workflows. One of the major successes in polar cyberinfrastructure is Quantarctica, a free GIS package and data collection built on QGIS and including a large and growing number of community-developed geospatial datasets packaged for interoperability; development of regional Arctic QGIS-based GIS packages would be a boon to the community*." QGreenland will be the first step in developing this Arctic QGIS data package, with further development expected through continued project partnerships and follow-on grants.

NSF agency goals are also addressed by QGreenland. The NSF Navigating the New Arctic Big Idea "*promotes initiatives that empower new research communities, diversifies the next generation of Arctic researchers, integrates the co-production of knowledge, and engages partnerships, particularly among international stakeholders*". QGreenland engages international partners to provide a tool to empower new, interdisciplinary research communities and results ("*at the intersections of Arctic natural and built environments and social systems*"), with open access supporting a diverse user group. Bringing together interdisciplinary Greenland-focused data and ensuring that it is discoverable, useable, interoperable, and well-supported also supports the NSF Harnessing the Data Revolution Big Idea goal to "*enable new modes of data-driven discovery that will allow fundamental questions to be asked and answered at the frontiers of science and engineering*". We also expect QGreenland to be a useful tool for logistics groups as they implement strategic plans for Polar Regions (NSF Advisory Committee for Geosciences, 2014). Finally, QGreenland aligns with EarthCube's aim "*to create a well-connected and facile environment to share data and knowledge in an open, transparent, and inclusive manner, thus accelerating our ability to understand and predict the Earth system*."

Other U.S. needs are also addressed through QGreenland. The U.S. Arctic Research Commission (2017) has identified the need to "*advance multidisciplinary research, involving engineering, socioeconomics, and climatology, among others*", and "*recommend improved methods for data sharing among research entities*." The National Research Council (2015) also notes that "*the need for actionable Arctic research has never been greater than it is today*," and that "*for the people who are living the reality of the changing Arctic every day, it is crucial to be able to act on what is learned from research*" (National Research Council 2015). QGreenland directly addresses these needs by integrating a wide range of environmental data into an open-source, plug-and-play package that diverse Arctic stakeholders can use to access research results and make decisions.

QGreenland also responds to international needs and priorities. The 3rd International Conference on Arctic Research Planning highlighted the need to drive research by "*supporting international efforts to make Arctic data and metadata easily accessible*" and "*disseminat[ing] [Arctic] knowledge by ensuring access to research data and results*" (IASC 2015). Similarly, one of the themes of the 2nd Arctic Science Ministerial included "Facilitating Access to Arctic Data" (ASM2 2018). The report identifies an urgent need to better understand the changing Arctic environment and to "*enhance multilateral scientific cooperation between Arctic and non-Arctic States, Indigenous Peoples, local communities, and societal and economic stakeholders*." It also notes that "*existing national and international observing and*

research efforts and data management initiatives are not yet fully able to meet the demand for sustained, comprehensive, and integrated information on the Arctic." QGreenland will reduce these disconnects.

With distribution via the QGreenland Team, Project Collaborators, Editorial Board, website, email list serves, etc., we project widespread adoption of QGreenland as a fundamental research tool:

- QGreenland provides an instant in-field tool with a full set of reference data. Many locations in Greenland have no or very limited internet access, including populated regions.
- GIS is a powerful visualization tool. We expect immediate adoption of QGreenland to support, for example, the NSIDC Greenland Today project, which provides up-to-date information on Greenland Ice Sheet melt, mass loss, and climate-ice sheet interactions. A widely-recognized resource, Greenland Today has received >1.6 million unique pageviews since its 2012 inception (almost 1 million in the last three years), with a primary audience in the US (32%), UK (9%) and Canada (6%).
- QGreenland is an ideal tool for geoscientists to use for interdisciplinary and systems-focused science, a growing emphasis for NSF research, as demonstrated by the recent Navigating the New Arctic solicitation and Coastlines & People initiative. With QGreenland development based at NSIDC, the NSIDC science team has enthusiastically agreed to act as early adopters. We have received a similarly eager response from other Project Collaborators (e.g., Paul Morin at the Polar Geospatial Center stated, "It took me 5 minutes for a bunch of PGC to say yes", and NPI, the developers of Quantarctica, have received many requests to develop a QGreenland tool). Expected uses include visualization (for publications, online use, and proposals), base environment for individual projects (e.g., on Greenland ice sheet motion and ice sheet-ecosysem interactions), and as a tool to explore system science, including across geoscience, social science, and the built environment.

4. BROADER IMPACTS

Serving researchers, educators, decision makers and planners, and communities, the broader impacts of QGreenland are far reaching.

Along with addressing NSF GEO Imperatives & Frontiers 2015-2020 goals in research and data, QGreenland also supports Education & Diversity goals. QGreenland can help increase undergraduate exposure to geoscience via use in GIS courses, and the interdisciplinary data environment of QGreenland provides a natural entry point for "*identifying research directions that are relevant to communities and as a bridge between basic research and community-relevant science*". QGreenland will provide an ideal package for teaching about Greenland but can also be used as a topical theme for teaching GIS skills more broadly. This multi-functionality will make QGreenland attractive for a variety of educators across the middle school to university level.

To support successful educational outcomes we will create and include 3 or more QGreenland-based lesson plans, with a minimum of one each for middle, high school, and college students. We will also encourage QGreenland users to submit further activity plans and suggestions, with these accessible in an online community space. An educator-focused QGreenland Training Workshop will be presented at the Colorado Science Conference. We will also provide a virtual educator QGreenland Training Workshop, to be recorded and posted online, with an initial target audience of the NOAA Planet Stewards Educator Project (online meeting attendance is ~150). We will also share these materials with stemteachingtools.org, an NSF-funded educator resource; they have identified a need for datasets teachers can work with easily, and QGreenland can serve this need. We will consider further co-writing of science materials with stemteachingtools.org. The Education Developer will also connect with the Advancing Coherent and Equitable Systems of Science Education (ACESSE) project, a collaboration among CU Boulder, U Washington, and the Council of State Science Supervisors, to inform education activity development in regards to encouraging equity.

With QGreenland and QGIS as free, cross-platform, open-source tools, QGreenland can help people in developing countries, under-resourced communities, and schools to learn about and conduct work

about Greenland. Typical GIS software is expense, so providing QGreenland for free, and using a free package platform, is a substantial socio-economic value that facilitates rapid adoption by, for example, users at community colleges and organizations and stakeholders with tight budgets. QGreenland also goes beyond the basics available in online tools and is a tool that will help take Greenland from the more remote to the more explorable.

While research in the north can often be extractive, by co-creating a flexible architecture on an open platform with open data, QGreenland has the potential to deliver "southern" data back north, rather than the other way around. QGIS also supports translation of the QGIS interface into other languages (~40 at present), and we have reached out to them to explore the possibility of a Greenlandic translation. We will pursue this option if feasible. PI Moon and Co-PI Pope will also intentionally foster diversity and inclusion in the QGreenland Team and QGreenland community, working towards gender representation and to achieve Indigenous & Greenlandic inclusion and co-development of QGreenland. We will engage thoughtfully with QGreenland Project Collaborators, the Editorial Board, and workshop participants on these goals.

QGreenland will also support data and software progress. Quantarctica developers found that developing Quantarctica produced an important foundation for community development of related tools in other software packages. With the most difficult work – finding, modifying, and serving diverse data – already completed by Quantartica developers, others created or improved Antarctic tools for R (QuantarcticR, also open source) and Matlab (proprietary). In this way, as an open-source package, QGreenland creates a base for further dissemination of key datasets and useful research tools. As an interdisciplinary but regionally-focused GIS package, QGreenland is also well-positioned to connect across a range of EarthCube efforts, via direct collaboration with the EarthCube Polar Computing RCN and GRISO network, and sustaining P418 practices through our NSF ADC connection. PI Moon and Co-PI Pope are both part of previous or current EarthCube projects, and are familiar with the community and EarthCube vision, which QGreenland will support.

Finally, through open communications with Natural Resources Canada and Hatfield Consultants, who are working on QGIS starter kits for Canada and the Canadian Arctic, we will begin to connect users across communities. Their user needs assessments and pilot experiences will also inform creation of QGreenland. This coordination will help advance the vision of creating a full QArctic package suite. Scaling up QGIS packages to the whole Arctic will also benefit from future coordination with the Arctic Spatial Data Infrastructure.

5. MANAGEMENT PLAN

The QGreenland Team is based at the University of Colorado Cooperative Institute for Research in Environmental Sciences (CIRES) NSIDC (a CIRES center) and includes experts in Greenland research (covering geosciences and social sciences), data management and archive, outreach and education, and project and community management and evaluation. Maintaining the core QGreenland Team within CIRES allows us to use established CIRES/NSIDC administration, communication systems, and organizational structure to develop QGreenland efficiently and effectively. Consulting Developer George Roth is the only non-CIRES Team member, providing valuable knowledge based on his role as a primary developer for Quantarctica. Project Collaborators and the Editorial Board provide other key links to organizations, individuals, and communities outside of CIRES.

5.1 Sustainability Plan

QGreenland package sustainability is an important issue. While full development for the QGreenland package, including data collection, modification and archive, dissemination, training material development and delivery, and all activities outlined within this proposal can be completed within the 3-year grant period, longer-term sustainability is a challenge. To meet this challenge, QGreenland will be fully developed on and shared via open-source software, with transparent development code and

standards. QGIS is a platform that facilitates sustainability. QGIS is based upon a large ecosystem of plugins and packages and therefore must maintain consistency or risk losing large swathes of functionality. The developers of QGIS strive for compatibility between versions, and they clearly document critical issues between major versions. The vibrancy of the QGIS community will facilitate the sustainability of QGreenland.

All data used in QGIS will be managed with FAIR data practices, which will ensure that the work done in compiling data for QGreenland can also be used in the future. All datasets in QGreenland will be archived at the NSF ADC, where data managers and user services experts will help to ensure that all data are well-described (see Data Management Plan). Ensuring that these data are discoverable and citeable will mean that the building-blocks of QGreenland will be sustainable into the future. Incorporating functionality in QGreenland for Category 3 web-served data, in addition to Category 1 and 2 locally hosted data (section 2.2), also enhances the package's sustainability. By including web-served data, QGreenland can be updated with the latest dataset versions with no addition QGreenland Team interaction.

These open access practices will be paired with substantial user community development, including online space for users to contribute, discuss, and interact with the QGreenland Team and each other. During the grant period we will explore the most effective platform(s) for creating and maintaining this interactive community and providing full transparency; for example, via an Interagency Arctic Research Policy Committee (IARPC) user group, GitHub, QGreenland website, listserv, etc. We will encourage users to contribute additional GIS tools to QGreenland and ask users to consider supporting dataset updates and software updates after the NSF grant finishes. The QGreenland website will include suggestions, resources, and vision for how users can further QGreenland success. It is possible that additional funding will be sought, via NSF or other organizations, to support further development (e.g., for building out the QArctic vision) and updates, but the package and proposal developed here does not depend on continued funding.

QGreenland is also a stepping-stone to future development of Greenland and Arctic GIS platforms that leverage not just cloud-served data but also cloud-powered analysis tools. QGreenland is designed primarily for offline use, but as Arctic connectivity increases, a future version of QGreenland could leverage partnerships with established players in this space including Lockheed Martin, Google EarthEngine, and Amazon Web Services. Already, these platforms are incorporating datasets relevant to Greenland and the Arctic. The work done by QGreenland can also help these players identify important and authoritative datasets to include in their platforms. Other key GIS infrastructure (e.g. by data- and service-provider Boundless, the government provider for Planet satellite data) are also built on QGIS, bolstering community use and knowledge of QGIS.

5.2 Metrics & Assessment

Developing and tracking metrics for QGreenland is necessary throughout the project lifetime to inform package development, determine primary user groups, target outreach and education to expand users, and evaluate project success. NSIDC personnel and the QGreenland Team include experts in developing and evaluating data metrics. We will leverage this expertise to maintain responsive and useful metrics for QGreenland. Expected metrics include download tracking (for full package and individual layer downloads), community interaction metrics, assessment of in-person and online engagement, size and diversity of mailing list and online community members, citation tracking for QGreenland and QGreenland datasets, and statistics on data contributors and workshop participants. Trends for all metrics will be evaluated at least every 6 months and used to revise development, dissemination, and training plans as needed. All metrics will be made publicly available on the QGreenland website.

The Project Team includes a professional Evaluator who will support development and delivery of evaluation material, including workshop evaluations, online user evaluations, community surveys, one-

on-one user evaluations (including educators and stakeholders). The Evaluator will also help with interpretation and application of results for QGreenland improvement.

5.3 Project Timeline & QGreenland Team

The Project Team will be based at CIRES/NSIDC at the University of Colorado, Boulder. Those positions that do not already have named experts will be filled through a combination of current CIRES/NSIDC staff and contract positions that may combine funding from this proposal with other funded projects.

Activity	Year 1		Year 2		Year 3	
Develop user group & mailing list						
Form QGreenland website						
Community surveys						
Form Editorial Board						
Quarterly Editorial Board meetings						
Collect and structure data						
Build QGreenland package						
Finalize QGreenland package & metadata						
QGreenland community building						
QGreenland Training Workshops						

Figure 5. Project timeline.

PI Twila Moon is a NSIDC Research Scientist specializing in Greenland glaciology, Arctic system science, and remote sensing, and is an avid GIS user (including Quantarctica). She is active in development of the Greenland Ice-Ocean Observing System and an Acting Committee member for the Greenland Ice Sheet Ocean Science Network (GRISO), including Co-PI of the recent GRISO EarthCube RCN. Moon will act as primary project lead, coordinating project organization and management, leading and supporting activities across the project.

Co-PI Allen Pope is a NSIDC Research Scientist and Executive Secretary of the International Arctic Science Committee. His research specialty is polar remote sensing, including substantial GIS use. Pope is an AAAS Community Engagement Fellow and Co-PI of the EarthCube Polar-Computing RCN. Pope will work with Moon in leading, coordinating, and developing all QGreenland activities and Team members, and act as a direct liaison between QGreenland and IASC.

The **Scientific Developer** (TBD) will collect data from contributors and data centers based on PI and user recommendations; create the workflow for data ingest, including resampling, reprojection, and reformatting; ensure metadata and data provenance is preserved and included with the data and that data management aligns with the data management plan; build the redistributable QGreenland package for both online and offline usage; and may help to provide training and user support for the QGreenland application and address issues and feature requests.

The **Communications** expert (TBD) will develop and maintain the QGreenland website; manage the online collaboration platform and email list communication; provide communications and recruitment activities for social media and online sharing; and develop training and dissemination material.

The **Education Developer Kathryn Boyd** will develop 3 or more curriculum activities for middle, high school, and college teachers, support outreach and QGreenland Training Workshops for educators, and consult on overall training material development and use.

The **Evaluator Katya Schlosser** will advise on project evaluation activities, best practices, and materials, including help with design, information gathering, and interpretation of project metrics, and application of findings to maximize QGreenland success.

Consulting Developer George Roth was formerly developer and project coordinator for Quantarctica version 3 at NPI as well as a polar geospatial support specialist at the PGC. He is now a GIS expert in the non-academic public sector and will provide consultation on QGreenland development and activities.

The **Operations Administrator** (TBD) will incorporate support for the product into the NSIDC infrastructure. They will reserve, register, and request a web security certificate for the domain, deploy the web proxy configuration to the enterprise web servers, configure status monitoring tools, systematically validate data consistency, and provide daily backup protection for recovery.

6. RESULTS FROM PRIOR NSF SUPPORT

PI Moon: Moon is an early career scientist. She is Co-PI on an NSF EarthCube Research Coordination Network grant and received an NSF Graduate Research Fellowship and NSF OCE Postdoctoral Fellowship (2015-2016). **Grant**: EarthCube RCN: Collaborative Research: Engaging the GrIS Ocean (GRISO) Science Network. ICER 1743687, $299,000, 5/1/2017 - 7/31/2018 (currently in 1-year extension period). **Intellectual Merit:** Activities to date include: 1) Facilitated ocean bathymetric data release from individual PIs and national repositories for a new Greenland bathymetry (Morlighem et al. 2017); 2) ISMIP6 engagement to provide ocean forcing for AR6 IPCC ice sheet modeling simulations (presented at pre-AGU ISMIP6 meeting); 3) Progress on a prototype fjord/glacier database as a framework for Greenland ocean, atmosphere, glaciology data integration; 4) National and international community engagement in the establishment of GrIOOS – a Greenland Ice Ocean Observing System (Straneo et al. 2018); follow-up discussion workshops at AGU 2017 and 2018; and engagement with the International Ocean Observation Commission (IOOC). **Broader Impact:** Community-wide activities by this RCN are enabling progress to address Greenland's sea level rise contribution and impact on the ocean. Central to the RCN activities is promoting data access (e.g. the bathymetric datasets) and best data sharing and collection practices (e.g. GrIOOS and a sample data node). **Publications/Presentations**: Moon et al. 2017, Morlighem et al. 2017, Moon et al. 2018, Straneo et al. in review (*Frontiers Marine Science*). Presentations for: EarthCube, IARPC, 2017 and 2018 AGU Fall Meetings, and IOOC.

Co-PI Pope: Pope is an early career scientist and is a PI on an active Antarctic Glaciology grant, Co-PI on an EarthCube RCN, and an NSF Graduate Research Fellow. **Grant:** EarthCube RCN: Collaborative Research: Research Coordination Network for High-Performance Distributed Computing in the Polar Sciences. ICER 1541620, $44,472, 9/1/2015-7/31/2018**. Intellectual Merit:** This RCN aimed to connect the Polar Science, Data and High-Performance and Distributed Computing (HPDC) communities to enable deeper penetration of computing methods and cyberinfrastructure into the polar sciences. Activities included: 1) Polar Imagery Workshop (Spring 2016), 2) XSEDE Polar Hackathon (2016), 3) HPC Training & Hackathon (Summer 2017), 4) Polar2018 Software Carpentry Intro to HPC Workshop, and 5) Polar2018 Session. **Broader Impacts:** Activities from this RCN have helped train and inform members of the polar research and computing communities, enabling research which would otherwise have been impossible or unfeasible. The RCN resulted in another RCN specifically focused on unique challenges related to high resolution imagery in polar research. A report will detail challenges and recommendations for continuing the RCN's work initiated; bringing these communities together in a sustained, multi-dimensional engagement has the potential to inform HPDC development and transform polar science research. **Publications & Presentations:** Wyngaard et al. 2017. Final community report in progress with lead PI. Presentations for EarthCube All Hands, AGU Fall Meeting, Arctic Science Summit Week, Polar2018, & University of Colorado.