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Changes in the coastal environments and their impact on society in the Qaanaaq region, northwestern Greenland

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ABSTRACT

Coastal environments in the Arctic are increasingly affected by the rapidly changing climate. Significant and complex impacts of atmospheric warming have been intensifying, with changes observed both in terrestrial and marine environments. Here, we describe the overview and highlight the study results of multidisciplinary research activities performed under the ArCS II project (Arctic Challenge for Sustainability II) in the Qaanaaq coastal region of northwestern Greenland. The Japanese Arctic projects GRENE-Arctic and ArCS have conducted research at this study site since 2012. In continuity with these previous efforts, field and satellite measurements were carried out to quantify glacier and ice sheet changes. Fish, marine mammals and seabirds, which are key natural resources to human livelihoods, were studied in collaboration with local fishermen and hunters to examine habitat use and clarify the potential responses of marine ecosystems to the changing environments. Greenlandic villages are also directly affected by the flooding of glacial streams and landslides, which were monitored to better understand the driving mechanisms and risks to Arctic societies in the future. Research was also carried out in Qaanaaq village to investigate waste management and housing conditions. The study results were shared with residents through workshops that took place in Qaanaaq and nearby smaller villages. Our

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results show that coastal environments in northwestern Greenland are changing with increasingly evident impact on human livelihoods. Further collaboration with the villagers, notably in co-designing research questions and interests, is crucial to anticipate, reduce and mitigate the impacts of environmental changes on Arctic communities.

1. Introduction

Coastal areas in the Arctic are critically important for ecosystems and human activity (Forbes, 2011). These habitats are characterized by a relatively rich biodiversity and high productivity, which provide fundamental resources for people living in the Arctic. Because of the accessibility to the ocean and resources, Arctic settlements are typically distributed along the coast. Despite their fundamental importance for biodiversity and society, coastal areas in the Arctic are particularly sensitive and vulnerable to climate change. Sea ice, glaciers and permafrost are rapidly melting under a warming climate (Irrgang et al., 2022). Loss of sea ice leads ocean waves to cause erosion, and thawing permafrost causes destabilization of coastal cliffs and slopes (Nielsen et al., 2022; Lim et al., 2020). On the other hand, glacial discharge carries increasing amounts of sediments, which results in a seaward advance of the coast due to delta development (Bendixen et al., 2017).

In Greenland, more than 80 % of the land is covered by ice, and the remaining seasonally ice-free coastal areas are inhabited and used by a population of ~57,000 people. Greenlandic coastal environments are severely affected by climate change. Glaciers are melting and glacial meltwater discharge is affecting fjord environments, resulting in a wide range of impacts on the marine ecosystem (e.g. Hopwood et al., 2018). Steep slope terrains along the coast are thought to be destabilized by thawing permafrost and more frequent heavy rain events. Such changes in natural environments are of serious concern to Greenlandic residents. Increasing glacial melt causes streams to flood (Mikkelsen et al., 2016). Settlements at the foot of steep slopes are threatened by landslides and associated tsunami hazards (Gauthier et al., 2018; Svennevig et al., 2020). Accordingly, increased damage to buildings and infrastructure have been reported. Additionally, natural environments are influenced by social change, forming a complex set of interactions among the components of the coastal socio-ecological system (Schlegel et al., 2023)

To investigate changing coastal environments and their impact on Greenlanders, we have been conducting research in Qaanaaq, a village in northwestern Greenland (Avanersuaq), since 2012 (Sugiyama et al., 2017, 2020, 2021). These activities have been carried out in the framework of the Japanese Arctic research projects GRENE (Green Network of Excellence, 2012–2016), ArCS (Arctic Challenge for Sustainability, 2015–2020) and ArCS II (2020–2025). The initial focus of the project was scientific study of glaciers and ice sheets (Podolskiy et al., 2016; Podolskiy, 2020; Sakakibara and Sugiyama, 2018, 2020; Seddik et al., 2019; Sugiyama et al., 2014, 2015; Tsutaki et al., 2016, 2017). The study of marine-terminating glaciers was expanded to include ice-ocean interactions and glacier influence on the marine ecosystem (Kanna et al., 2018; Naito et al., 2019; Nishizawa et al., 2019; Matsuno et al., 2020). Motivated by exchanges with local collaborators during field activities as well as our own observations and experiences in the region, we began working on community related research topics such as marine resources, natural disasters, living environments and traditional way of life. In the latest project (ArCS II), we assembled a research team of marine biologists, glaciologists, geophysicists, engineers, and social scientists, to address multi- and interdisciplinary research topics. In this manuscript, we introduce an overview of the research activities performed as part of the ArCS II research project “Arctic Coastal Change and Its Impact on Society”.

2. Study site

Qaanaaq (77°28′ N, 69°14′ W) is situated in the Avannaata municipality in northwestern Greenland (Fig. 1a) populated by approximately 650 residents (Hastrup et al., 2018; Nuttall, 2020). The village was established in 1953 when population of Pituffik and Dundas was relocated. The region is accessible by flight to Qaanaaq Airport and local transport primarily includes boats, snow mobiles and dog sledges. In this region, snow and ice related research activities have been carried out by Japanese researchers since around 2000 (e.g., Matoba et al., 2002; Uetake et al., 2010; Aoki et al., 2014). The village is located on the coast of a peninsula, which is covered by Qaanaaq Ice Cap (260 km^2) except for its coastline (Fig. 1b) (Søndergaard et al., 2019; Carrivick et al., 2023). Bordering the village is the entrance to Inglefield Bredning, a ~100 km long, ~20 km wide and >900 m deep glacial fjord system (Fig. 1a) (Willis et al., 2018). Sea ice covers the fjord during winter until it breaks up in spring, generally in July. Sea ice seasonality is crucial for the local community because it enables people to use dog sledges, cars and snowmobiles. The timing of sea ice break-up is of great interest to the residents because hunting of marine mammals takes place along the edge of sea ice, as well as the first supply ship of the year can dock as soon as the sea ice allows it. Because several marine-terminating glaciers feed the fjord (Porter et al., 2014; Hill et al., 2017), icebergs are abundant near the village. They are utilized as a freshwater resource in wintertime. An important environmental feature in northwestern Greenland is the North Water Polynia (Pikialasorsuaq), the largest recurrent polynia situated in northern Buffin Bay (e.g. Barber et al., 2001). A large areas of open water play key roles in marine biology as well as ocean and atmospheric processes in the region (e.g. Melling et al., 2001). Therefore, the ecosystems and human activities are strongly influenced by the marine productivity and climate sustained by the formation of polynya (Hastrup et al., 2018; Ribeiro et al., 2021; Hornby et al., 2021; Gillie et al., 2024).

Several smaller settlements are found in the Qaanaaq region. Siorapaluk is situated ~50 km northwest from Qaanaaq on the coast of a glacial fjord connected to Baffin Bay. A large colony of little auks (*Alle alle*) is situated near the settlement, where residents catch seabirds with a traditional hand net (Mosbech et al., 2018). Qeqertat is a settlement situated ~60 km east of Qaanaaq in the inner part of Inglefield Bredning. The area close to Qeqertat is a key site for narwhal (*Monodon monoceros*) hunting during the summer (Heide-Jørgensen et al., 2010; Hansen et al., 2024) and halibut (*Reinhardtius hippoglossoides*) fishing during the winter (Flora et al., 2018). These settlements are populated by ~20–30 people each (Hastrup et al., 2018).

3. Study results

3.1. Marine biology

Marine environments surrounding Qaanaaq are influenced by glaciers and sea ice (e.g., Straneo et al., 2022). Thus, increasing ice melt may affect the marine ecosystem, which is important for fishing and hunting in the region. To examine the links between marine environments, changing glaciers and the community, we measured oceanographic characteristics and analyzed biological samples in glacial fjords. Following biogeochemical research performed in the ArCS project (Sugiyama et al., 2021), we have expanded our ocean study to include marine biology.

In August 2022, the autonomous Acoustic Zooplankton Fish Profiler (ASL Environmental Sciences) echosounder was moored near the ocean floor at ~1 km from the front of Bowdoin Glacier (Kangerluarsuup Sermia) (Fig. 1b). This echosensor emits acoustic waves (38 and 200 kHz) upward to locate distributions of zooplankton and fish between the sensor and the water surface. After a year of data collection, the instrument was retrieved in the summer of 2023 (Fig. 2a). Preliminary data analysis shows a dense population of zooplankton and fish during the summer, whereas biological activity was sparse in the winter. Diurnal migration in the vertical direction was observed between the periods of the midnight sun and polar night, suggesting an influence of circadian solar radiation on marine life. To our knowledge, similar measurements have never been taken in such close vicinity to a marine terminating glacier, so new insights are expected into the influence of a glacier on the fjord's marine biological activity.

Greenlandic halibut and Arctic char are two of the most popular catches in the region. In collaboration with fishermen in Qaanaaq, we learned about the techniques and instruments used for fishing these species. Greenlandic halibut fishing is commonly carried out in spring using a longline that is set from a hole drilled through sea ice, which has recently become economically most important fishery in the region (Hastrup et al., 2018; Flora et al., 2018). To stretch the longline horizontally under sea ice, fishermen use a metal plate which glides in the water current. With an accelerometer attached to a kite (0.48 m × 0.72 m, 2.7 kg), the motion during longline deployment was measured for the first time (Tanaka et al., 2024). The measurement confirmed that the gliding motion of the plate enabled the longline (3.0 mm in diameter) to be stretched for several hundred meters from the deployment site. The data also showed that the horizontal extent of the longline is maximized by the weight balance of the plate and careful handling of the string, examples of traditional Arctic knowledge. We also observed gillnetting fishing of Arctic char. Fish sample sizes indicate increased body height from July to August, whereas the change in fish length was insignificant. This result suggested that the summer period is important for Arctic char to store body fat and gain weight.

Hunting marine mammals is a traditional subsistence activity in Greenland. Seals are the most important catch in Greenland, not only as a source of food but also material for traditional clothes and tools. Despite their importance in this context, the habitat and behavior of seals are not yet well understood, particularly in northwestern Greenland. In collaboration with local hunters and the Greenland Institute of Natural Resources (GINR) in Nuuk, GPS (global positioning system) and CTD (conductivity, temperature and depth) sensors were tagged on seals in the summers of 2021 and 2023 to study their behavior and travel throughout their marine habitat (Fig. 2b). Data acquired from four ringed seals (*Pusa hispida*) through a satellite communication system revealed their habitat use was largely influenced by sea ice and marine terminating glaciers (Sakuragi et al., 2024). The seals' locations, depth and diving frequency were also analyzed and important insights into their foraging behavior were obtained. Collaboration with local hunters provided us with a unique opportunity to investigate the stomach contents of seals. Stomachs of 24 ringed seals provided by hunters during the summer in 2022 and 2023 were analyzed for information about their diet and any links with foraging grounds (Ogawa et al., 2024). The study results indicate the importance of the marine-terminating glacier front for seals' feeding and the potential impact of glacier retreat on marine mammals and the fjord ecosystems.

In northwestern Greenland, people catch narwhals in a traditional

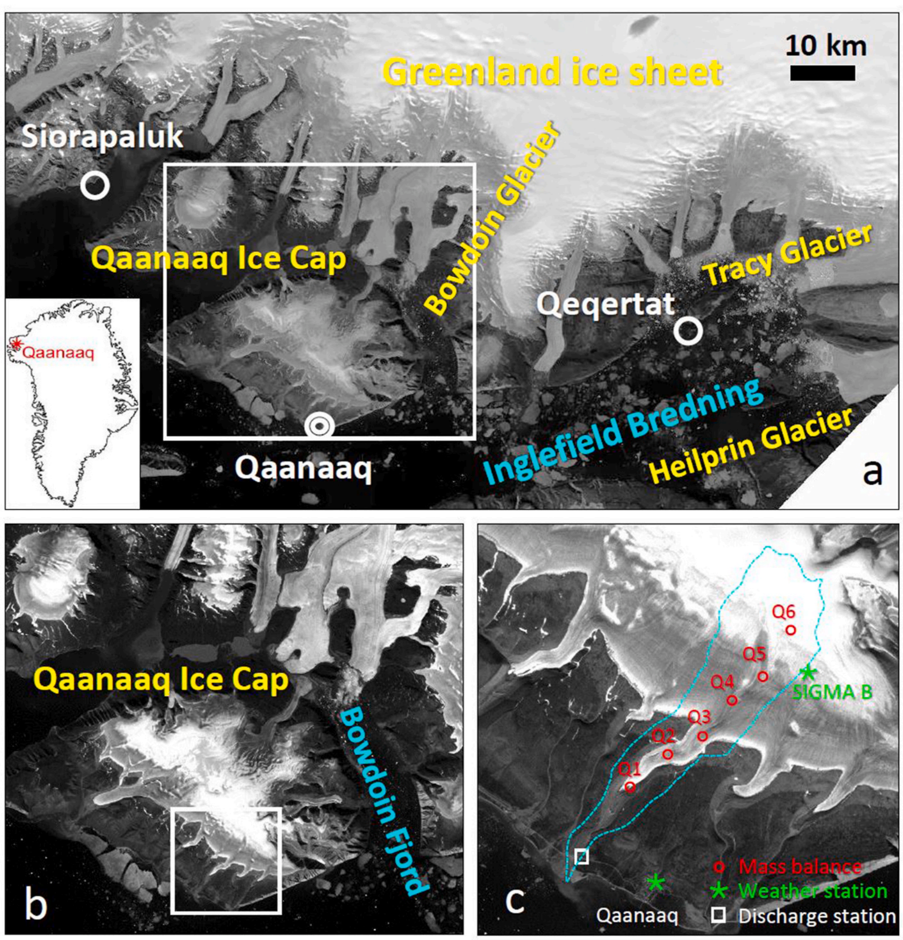

Fig. 1. (a) Satellite image showing region of study in northwestern Greenland (Landsat 9 on July 26, 2023). The inset shows the location of Qaanaaq. (b) Qaanaaq Ice Cap. (c) Mass balance and ice speed survey sites on Qaanaaq Glacier (○), weather (★) and discharge stations (□). The insets in (a) and (b) show the regions covered by (b) and (c), respectively.

Fig. 2. (a) Recovery of the Acoustic Zooplankton Fish Profiler at Bowdoin Fjord (July 31, 2023). (b) Logger tagging on a ringed seal in collaboration with GINR scientists at Inglefield Bredning (August 15, 2023) and (c) sampling biological tissues and organs from a narwhal harpooned by villagers at Qeqertat (August 5, 2022). (d) Interview with hunters in Siorapaluk (September 13, 2023).

way of hunting with a small kayak and harpoon (Fig. 2c). Narwhals behavior was investigated using underwater acoustic sensors. Following an initial short-term data collection period using a sensor hung from a boat (Podolskiy and Sugiyama, 2020), hydrophones were moored at the seafloor near the fronts of Bowdoin and Tracy Glaciers for medium- and long-term measurements (Podolskiy et al., 2021b). The instruments recorded high energy sound (>120 dB) caused by a glacier calving event and subsequent iceberg disintegration, which is assumed as the loudest type of underwater sound in the Arctic (Podolskiy et al., 2022). Despite the boisterous acoustic environment, the sound record confirmed marine mammal activity near the glacier front, including repeated physical interactions of narwhals with the moored device, primarily during the daytime (Podolskiy et al., 2024b). Biologging data previously acquired from a depth sensor attached to a narwhal in East Greenland also showed a higher likelihood of deep diving in the daytime (Podolskiy and Heide-Jørgensen, 2022).

Seabirds play a part of upper trophic levels of the marine ecosystem in the Arctic. Among the various seabirds inhabiting Greenland, we studied little auk, a key species in Arctic coastal regions (González-Bergonzoni et al., 2017). Northwest Greenland hosts the largest aggregation of the species on Earth, with many birds nesting in a large breeding colony near Siorapaluk (Fig. 1a and 3a) (Mosbech et al., 2018). An acoustic sensor installed in the colony showed diurnal variations in sound magnitude despite the environment of the midnight sun (Podolskiy et al., 2024a). This study is important to understand the rhythm of foraging and vocal interaction of little auks, as well as to demonstrate the potential of acoustic recording for bird observations. We also analyzed mercury concentration and plastic contamination in little auks, using samples collected with subsistence hunting methods by a local hunter in Siorapaluk (Otsuki et al., 2024). Higher mercury concentrations (~3.5 μg g^{-1}) were found in the feathers of adult (>3 years old) and currently breeding birds. Macroplastic debris (~50 mg) was found in the stomachs of 15 % of samples (Fig. 3b and c), indicating the influence of anthropogenic emissions on the marine environment. The results are important to the local community, in order to reduce secondary ingestion of plastic debris as well as their risk of toxin intake (Dietz et al., 2018).

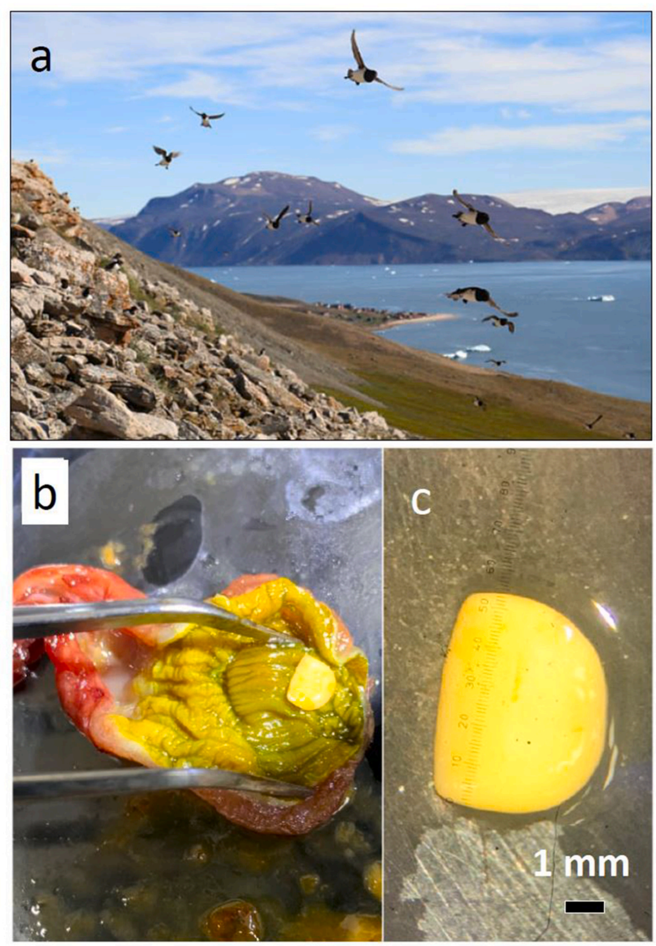

Fig. 3. (a) Seabird colony of little auks near Siorapaluk (July 31, 2016). (b and c) Plastic debris found in the stomach of a little auk sampled in Siorapaluk (adapted from Otsuki et al., 2024).

3.2. Glaciers

To quantify glacier mass loss in northwestern Greenland, mass balance monitoring has been carried out on Qaanaaq Glacier, a land-terminating outlet glacier of Qaanaaq Ice Cap (Fig. 1). The survey was initiated in 2012 and repeated annually in July–August. In 2020 and 2021 when our travel to Qaanaaq was prohibited by the COVID-19 pandemic, observations were carried out by collaborators from ASIAQ (Greenland Survey) and the Danish Meteorological Institute with the help of local Greenlanders (Fig. 4a). Annual surface mass balance was obtained at six locations along the glacier's central flowline (Q1–Q6 in Fig. 1c) by measuring aluminum poles drilled into the ice (Fig. 4b). The poles were surveyed by GPS for annual ice motion, which helps our understanding of the mechanism driving glacier changes. The eleven-year period of data showed mostly negative surface mass balance in the region of study (Fig. 4c). Although our measurements do not cover the entire accumulation area extending up into the high-elevations, our estimate of the glacier-wide mean specific mass balance is significantly negative, i.e. -0.45 ± 0.19 m a^{-1} for the period from 2012 to 2024 (Watanabe, 2023; Imazu, 2024). The magnitude of the mass loss is smaller than that reported for ice caps in the region from 2006 to 2010 (-1.1 m a^{-1}) (Saito et al., 2016), but is similar to that from 2003 to 2008 (-0.6 m a^{-1}) (Bolch et al., 2013). Year-to-year variations in the mass loss during our study period showed a more significant correlation with summer temperature than snow precipitation, and were measured at the SIGMA-B weather station operated on the ice cap at 944 m a.s.l. (Aoki et al., 2014; Nishimura et al., 2023). Therefore, recent mass loss is primarily driven by an increase in melting due to atmospheric warming. On Qaanaaq Glacier, we also performed in-situ measurements using GPS (Imazu and Sugiyama, 2023), drone (Ukai et al., 2023; Yamada et al., 2024) and ice radar surveys (Lamsters et al., 2024; Sato and Sugiyama, 2023). These glaciological measurements provided ice speed, surface elevation, ice thickness and bed geometry details, which are necessary to understand the processes driving glacier changes. We utilized the data to develop a numerical model to reconstruct past glacier change and project its future evolution (Imazu, 2024).

Glacier melt is relevant to the Qaanaaq community because the outlet stream of Qaanaaq Glacier occasionally floods and destroyed a road that connected Qaanaq village to Qaanaaq Airport (Fig. 5a and b) (Sugiyama et al., 2021). We utilized in-situ data collected on the glacier to develop a hydrological model, which computes glacier surface melt and discharge into the stream (Kondo et al., 2021). The model reproduced the discharge during the flood events in July 2015 and August 2016, which were ascribed to intensive melting and a heavy rain event (90 mm d^{-1}), respectively. Numerical experiments show a 3 × increase in summer discharge occurring with the 4 °C warming projected by the end of the 21st century. During the 2023 summer field campaign, stream discharge was increased by a rain event and the road was flooded out again (Fig. 5b). Using measured and modeled discharge data to influence construction is desired for building a more robust infrastructure. However, in situ discharge observations are too labor intensive; so we recently have been monitoring the sound of the stream as an effective proxy for runoff (Evers et al., 2022; Podolskiy et al., 2023).

We also studied the ice sheet's outlet glaciers in the region. By comparing a digital elevation model derived from aerial photographs taken in 1985 with those from more recent satellite observations, ice surface elevation changes were quantified for 16 glaciers terminating in Inglefied Bredning and smaller fjords connected to Baffin Bay (Wang et al., 2021). The elevation changes averaged over the glaciers showed a clear shift from a stable condition between 1985 and 2000 (0.14 m a^{-1}) to rapid glacial thinning in the subsequent period from 2000 to 2018 (-1.31 m a^{-1}). 21st century thinning is more rapid on the glaciers terminating in the Inglefield Bredning than those on Baffin Bay, suggesting the importance of glacier geometry and ocean depth on glacier dynamics. Further satellite data analysis was performed for supraglacial lakes on Heilprin and Tracy Glaciers, two of the largest outlet glaciers in Inglefield Bredning (Wang and Sugiyama, 2024). The maximum lake area over eight melting seasons from 2014–2021 shows significant year-to-year variations (7.5–12.4 km^2 on Heilprin and 1.7–4.1 km^2 on Tracy Glacier), depending on the weather conditions during the summer. Lake formation is expected to occur further inland under a warming climate, leading to melt increase as a result of enhanced absorption of solar radiation.

In addition to the field and satellite observations performed over the

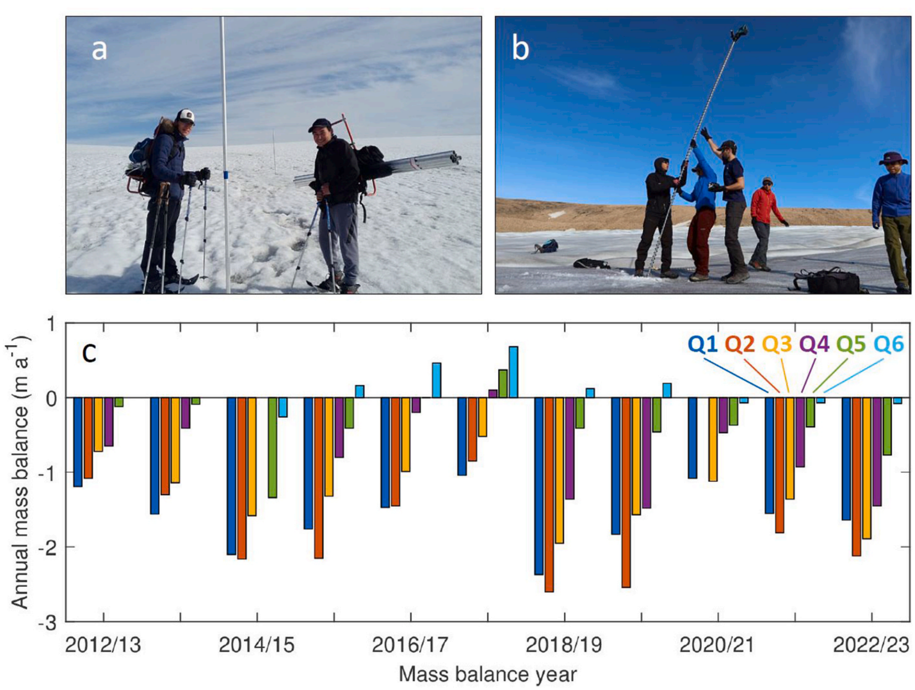

Fig. 4. (a) Taking mass balance measurements in collaboration with Qaanaaq residents (August 2, 2021) (b) and stake installation on Qaanaaq Glacier (July 28, 2023). (c) Surface mass balance at six locations on Qaanaaq Glacier (Q1–Q6 in Fig. 1c) for the mass balance years from 2012/13 to 2022/23.

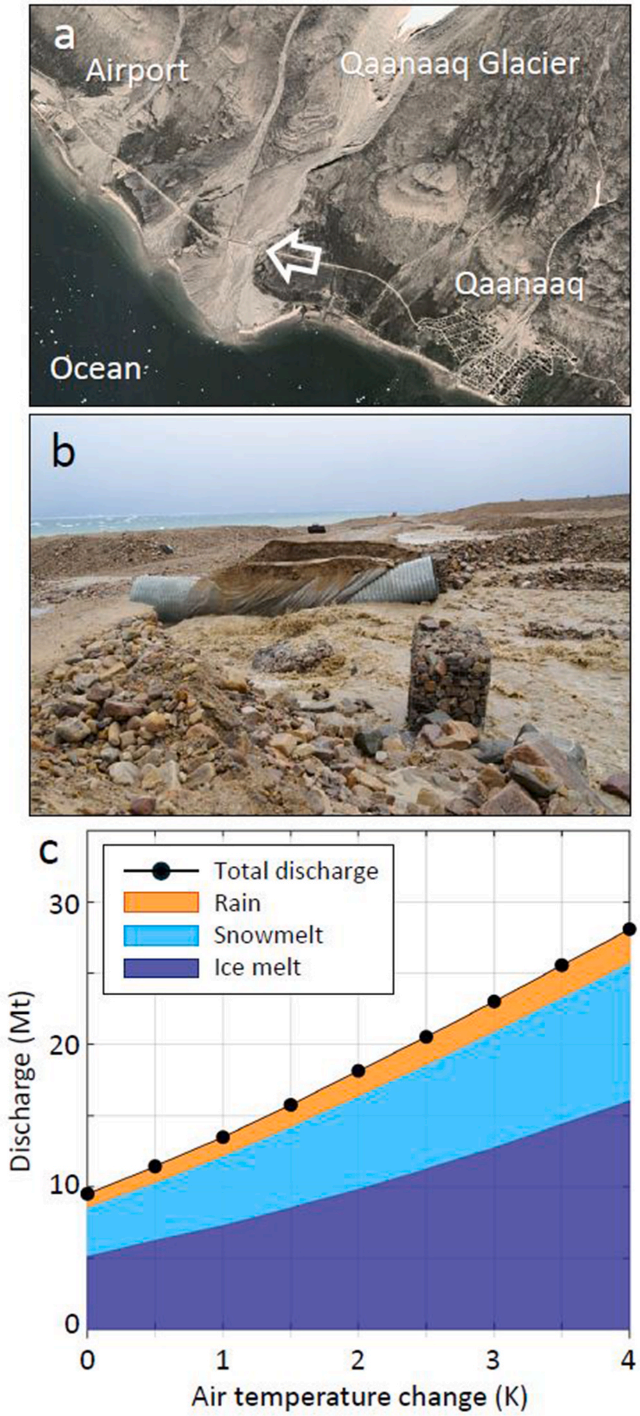

Fig. 5. (a) Satellite image showing the road connecting the village with the airport in Qaanaaq. (Google Earth image taken August 15, 2017). White arrow denotes the location of the photograph shown in (b). (b) Destruction of the road due to flooding of an outlet stream from Qaanaaq Glacier (August 23, 2023). (c) Discharge from Qaanaaq Glacier computed by a model under warming conditions. The contributions of rain, snowmelt and ice melt to the total discharge are shown with different colors (modified from Kondo et al., 2021). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ArCS II project timeframe, we analyzed data and samples that were acquired in previous campaigns at Bowdoin Glacier and its fjord. An ocean bottom seismometer deployed at 640 m from the glacier provided a unique data set, which revealed details of seismic signals generated by calving events and glacier sliding (Podolskiy et al., 2021a, 2021b). Ocean measurement with CTD sensors hung from the glacier calving front revealed a complex water structure and current within a plume of upwelling glacial meltwater (Podolskiy et al., 2021c). Continuous GPS measurements on the glacier over six summer seasons from 2013–2019 were analyzed for short-term ice speed variations controlled by meltwater, tide and rain (Sugiyama et al., 2025). Water samples from Bowdoin Fjord and Inglefield Bredning were analyzed to investigate the role of subglacial discharge in the biogeochemical conditions in the fjords (Kanna et al., 2020, 2022; Hoshiba et al., 2024). These studies gave new insights into the glacier-ocean interaction, which suggested impacts of melting and retreating marine-terminating glaciers on the coastal environment in Greenland.

3.3. *Landslide, sea ice and meteorology*

In 2016 and 2017, heavy rainfall destabilized steep slopes along the coast of Siorapaluk and debris reached the village caused damage to buildings (Fig. 6a) (Walls et al., 2020; Watanabe et al., 2022). To identify the mechanisms underlying the events, field investigations were conducted using a drone, GPS, thermal camera and electric resistivity profiler. Electric resistivity measurements were performed in the landslide triggering area to survey the underground structure. Measurements along a ~100 m long survey section showed that the failure occurred in a region covered with permeable materials characterize by low resistivity, implying that permafrost thawing is a possible reason for the permeable geology (Fig. 6b–d). The results were used to update a hazard map, which was presented in a workshop held in Qaanaaq with residents in July 2024 and a meeting at a governmental office in Nuuk in December 2024.

Another example of the impact of climate change on this Greenland community is the breakup of sea ice during winter, which affects the use of dog sledges for hunting and transportation. Winter breakup of sea ice is happening more frequently in the Qaanaaq region. During a strong windstorm in December 2016, for instance, sea ice in front of Qaanaaq drifted away, along with fishing equipment left on the ice (Matoba and Yamasaki, 2018). To investigate sea ice conditions in the region, in-situ ice thickness measurements (Harada et al., 2024), aerial drone surveys (Watanabe and Tateyama, 2021), interval camera observations, and satellite data analysis have been performed. Further investigations are in progress on the relationship between sea ice and meteorological conditions.

To understand a link between changing natural environments in the Arctic and the warming climate, more frequent and broadly distributed atmospheric measurements are required. The use of a drone is a solution for inexpensive, technically less demanding and environmentally friendly observations in the atmosphere. Nevertheless, temperatures measured by a drone are often affected by heat and wind generated by airflow due to flight motion as well as from the drone itself. To overcome these problems, commercially available drones and sensors are tested and adjusted to reduce external influence on measurements (Inoue and Sato, 2021, 2022). A developed drone system was further refined for aerosol measurements and used for observations in the Arctic and Antarctica (Inoue and Sato, 2023).

3.4. *Waste management and housing environment*

Motivated by conversations with Qaanaaq residents during collaborative field activities and discussion in the workshops described in the next section, our research has been extended to include living environments in Qaanaaq. During the 2022 field campaign, we sampled and analyzed soil and water around the village dump site situated on the coast approximately 1 km from the village (Fig. 7a). This investigation was instigated as a result of the serious concern residents voiced about the potential threat of pollution. As anticipated from visual observations (Fig. 7b), pollutants were detected from the samples obtained from

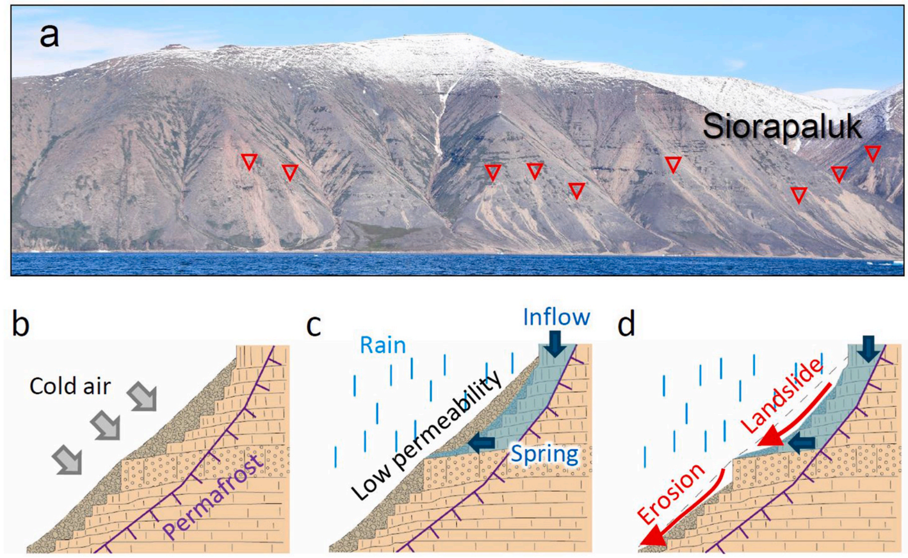

Fig. 6. (a) Photograph of the slope along the coast of Siorapaluk (July 20, 2018). Red triangle markers show the significant landslides. The horizontal distance in (a) is ~3 km. (b–d) Schematic diagrams showing a cross section of the slope and the landslide mechanisms occurring in Siorapaluk. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

surface water and soil in and around the site. Concentrations of heavy metals, such as lead and cadmium, were greater than the upper limit of standards. For example, when we conducted the leaching test according to Notification No. 46 of the Soil Contamination Countermeasures Act, 14 soil samples out of 30 showed anywhere from one to two orders of magnitude greater than the environmental quality standards for lead soil contamination in Japan (10 μg L^{-1}) (Fig. 7c). This initial result demonstrates an urgent need for continued investigation and implementation of mitigation measures. Since the site is located on the seashore, pollution may leach into the ocean. We immediately consulted the community to clarify their opinion about the results and their desire for further research. The community requested more detailed investigations and asked for assistance with improving the situation. Therefore, we organized meetings with environmental officials in the municipality and researchers in Nuuk to report the situation. A new dataset using additional samplings will be prepared to help necessary actions by the village and the government.

Considering the severe and cold environment during winter, housing is critically important for quality of life and health in the Arctic. In collaboration with residents in Qaanaaq and Siorapaluk, in-door air quality (temperature, humidity, concentrations of CO_2, particulate matters and total volatile organic compounds) was monitored with sensors installed in houses (Osawa et al., 2024). The results showed relatively clean and favorable living conditions throughout year (e.g., CO_2 level <1000 ppm). Air temperature was warm and steady at ~25 °C, implying the importance of building insulation. For a better understanding of the energy efficiency of buildings, numerical simulations are performed on energy consumption for heating. Our data and experiments should contribute not only to improve the performance of buildings but also to the introduction of renewable energy in the future (Pantaleo et al., 2022).

3.5. Social dimensions and community involvement

Life in Greenland has been adapted to the Arctic climate and environments, which are now rapidly changing. Therefore, studying traditional and indigenous knowledge in the region should help our understanding of the environments and their recent changes. To this end, we studied the traditional way of life in Greenland, represented by hunting, dog sledding, animal skins and furs. For example, the thermal properties of animal fur commonly used for traditional clothing were measured and compared with contemporary materials filled with down and feather (Kusaka et al., 2022). Experiments in a cold room showed the advantage of the traditional materials with ~3× greater breathability, which is essential for hunting activities in the Arctic. We also investigated the construction and materials used for dog sleds. Further, benefiting from our relationship with the people in the region, we interviewed hunters to learn from their experience and to find out more about changes in natural and social environments (Fig. 2d). The outcomes of these activities are anticipated to provide recommendations for a sustainable future in Greenlandic communities, as well as to enhance our understanding of the interconnections between rapid climate change and the natural and social environments in the Arctic.

A framework was developed for researching community dynamics in the context of climate change by comparing Greenland halibut fisheries in Qaanaaq in northwestern Greenland with a sheep farming community in South Greenland. We argue that social, economic, and environmental issues within local communities are magnified by changing climate patterns. Furthermore, emerging industries, such as fisheries and tourism in North Greenland, have been affecting the local economy and life (Hayashi and Delaney, 2024).

4. Community involvement

At the suggestion of our Qaanaaq collaborators, we organized the first workshops with residents in Qaanaaq in July 2016. Since then, this workshop become an annual opportunity to introduce our research activities and study results. These events are crucial opportunities for us to inform the community of our research activities as well as to gain valuable indigenous and local knowledge from the audience. To communicate with a variety of people, we use the translation help of our Qaanaaq collaborators.

In July 2022, August 2023 and July 2024, approximately 50–70 people joined our presentation and discussion in Qaanaaq workshops held in a school (Otsuki and Sugiyama, 2024). After the introduction of the project, the ArCS II researchers presented the overview and key results of their study (Fig. 8a). The audience's interest centered around marine ecosystems and pollution from the dump site. Fishermen asked questions about the habitat of Greenlandic halibut, which is becoming an increasingly important resource in the region because a local factory was recently connected to a global market through a Greenlandic company. The audience showed serious concern about the data obtained

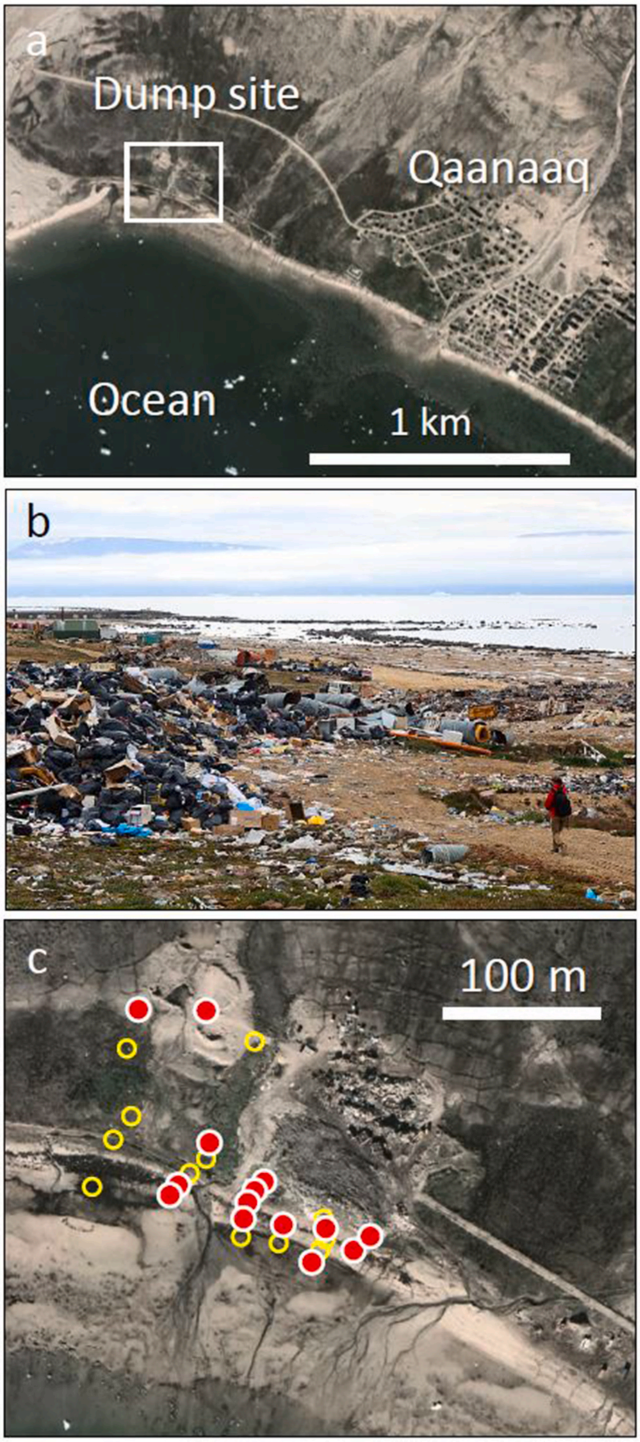

Fig. 7. (a) Location of Qaanaaq village and the dump site. (b) View of the dump site from the west (July 24, 2023). (c) Sites where soil was sampled in September 2022. Red dots show the locations where lead concentration exceeds environmental quality standards for soil contamination in Japan (10 μg L^{-1}). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

at the dump site (Fig. 8b). We agreed with the participants to continue the investigation and search for an opportunity to talk to the government for possible measures. As a first step forward, we visited Nuuk and Copenhagen in November–December 2024 for reporting and conversations with researchers in governmental institutions. We also met residents in the smaller nearby villages of Siorapaluk and Qeqertat (Fig. 8c). Collaborative research and communication with residents in small settlements is also an opportunity for local children to learn about the scientific method and natural environment from visiting scientists (Fig. 8d).

To reach a broader range of citizens, researchers and governmental officers in Greenland, we attended the Greenland Science Week in 2019, 2022 and 2023, where symposiums were held in the capital Nuuk. Northwestern Greenland is regarded as a region where Greenlandic culture is richly preserved, thus our research with local society drew attention of the symposium participants.

5. Conclusion and outlook

As a part of the Japanese Arctic research program ArCS II, multidisciplinary environmental studies were carried out in the Qaanaaq region, northwestern Greenland. Following the GRENE and ArCS projects which ran from 2012 to 2019, long-term measurements continued on glaciers, land and in the ocean. To study the impact of rapidly changing natural environments on human life, we have expanded our research to include the study of marine ecosystems, which traditionally support Arctic livelihoods. Issues directly connected to the community such as natural hazards and living environments were studied as well.

Ocean measurements indicated details of the influence of glacier melt on the biogeochemical conditions in glacial fjords. Fish, marine mammal and bird habitats were studied in collaboration with local fishermen and hunters. The results of these studies suggested an impact of glacier retreat on the marine ecosystem, which is an important and traditional resource for the community. Glaciers are losing mass at an accelerated rate in the 21st century. Marine-terminating glaciers are affected by changes in ice dynamics and interactions with the ocean, whereas those terminating on land are primarily affected by warming atmospheric conditions. Discharge measurements confirmed that increasing amounts of glacier melt and more frequent heavy rains are the cause of recent glacial stream flooding in Qaanaaq. According to the surveys at the landslide sites in Siorapaluk, increased ground permeability after permafrost thawing is a likely cause of the Siorapaluk landslides. Engineering researchers performed surveys on dump site pollution and housing air quality. Urgent action is needed on the dump site, where high concentrations of heavy metals were detected. These study results were shared in the workshops organized in Qaanaaq, Sioraparuk and Qeqertat. These meetings provided opportunities for the researchers and residents to determine future research priorities, as well as search for mitigation measures to lessen the impact on the changing environment.

Our research results provide key information about future changes along the Arctic coast. To ensure that our data are used to mitigate the impact on society, it is important to continue a dialogue with the local community. In conjunction with the subjects reported in this paper, several aspects such as health care, energy, education and tourism, are emerging as important research subjects in the Qaanaaq region. For example, the number of cruise ships operated along the Greenlandic coast is thought to be increasing (e.g., Long et al., 2023). Their impact on marine environment and Qaanaaq community is an urgent matter. Most importantly, the direction of future research should be determined in collaboration with local communities, residents and government authorities. Co-designing research projects with stakeholders is critical for the advancement of future Arctic research.

CRediT authorship contribution statement

Shin Sugiyama: Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Atsushi Yamaguchi:** Supervision, Project administration, Investigation. **Tatsuya Watanabe:** Supervision, Project administration, Investigation. **Yasumasa Tojo:** Supervision, Project administration, Investigation. **Naotaka Hayashi:** Project administration, Investigation.

Fig. 8. (a and b) Workshops in Qaanaaq on August 3, 2023 and (c) in Qeqertat on August 7, 2022. (d) Investigation of a seal's stomach contents with children in Siorapaluk (July 21, 2023).

Jean-Baptiste Thiebot: Writing – original draft, Investigation. **Makoto Tomiyasu:** Supervision, Investigation. **Kohei Hasegawa:** Supervision, Investigation. **Yoko Mitani:** Supervision, Investigation. **Mayuko Otsuki:** Investigation. **Yuta Sakuragi:** Investigation. **Monica Ogawa:** Investigation. **Kenzo Tanaka:** Investigation. **Kaisei Sakurai:** Investigation. **Naoya Kanna:** Investigation. **Evgeny Podolskiy:** Writing – original draft, Supervision, Investigation. **Ryo Kusaka:** Project administration, Investigation. **Yefan Wang:** Investigation. **Takuro Imazu:** Investigation. **Kaho Watanabe:** Investigation. **Ken Sato:** Investigation. **Shinta Ukai:** Investigation. **Soratakato Yamada:** Investigation. **Ken Kondo:** Investigation. **Shintaro Yamasaki:** Investigation. **Kazutaka Tateyama:** Investigation. **Kazutoshi Sato:** Investigation. **Jun Inoue:** Investigation. **Taro Mori:** Supervision, Investigation. **Tatsuya Fukazawa:** Supervision, Investigation. **Aqqalu Rosing-Asvid:** Supervision, Investigation. **Kirsty Langley:** Investigation. **Andrea M.U. Gierisch:** Investigation. **Jenna Sutherland:** Project administration, Investigation, Funding acquisition. **Toku Oshima:** Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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