Polar Science 27 (2021) 100632

Contents lists available at ScienceDirect

Polar Science

journal homepage: http://www.elsevier.com/locate/polar

# Rapidly changing glaciers, ocean and coastal environments, and their impact on human society in the Qaanaaq region, northwestern Greenland

Shin Sugiyama[a,b,*], Naoya Kanna[a,b], Daiki Sakakibara[a,b], Takuto Ando[a,b], Izumi Asaji[a,c], Ken Kondo[a,c], Yefan Wang[a,c], Yoshiki Fujishi[a,c], Shungo Fukumoto[a,c], Evgeniy Podolskiy[b], Yasushi Fukamachi[b,d], Minori Takahashi[b,e], Sumito Matoba[a,b], Yoshinori Iizuka[a,b], Ralf Greve[a,b], Masato Furuya[b,f], Kazutaka Tateyama[g], Tatsuya Watanabe[g], Shintaro Yamasaki[h], Atsushi Yamaguchi[b,i], Bungo Nishizawa[j], Kohei Matsuno[b,i], Daiki Nomura[b,i], Yuta Sakuragi[k], Yoshimasa Matsumura[l], Yoshihiko Ohashi[m], Teruo Aoki[j,n], Masashi Niwano[n], Naotaka Hayashi[o], Masahiro Minowa[p], Guillaume Jouvet[q,r,s], Eef van Dongen[q], Andreas Bauder[q], Martin Funk[q], Anders Anker Bjørk[t], Toku Oshima[u]

[a] Institute of Low Temperature Science, Hokkaido University, Nishi8, Kita19, Sapporo, 060-0819, Japan
[b] Arctic Research Center, Hokkaido University, Nishi11, Kita21, Sapporo, Hokkaido, 001-0021, Japan
[c] Graduate School of Environmental Science, Hokkaido University, Kita10, Nishi5, Kita-ku, Sapporo, 060-0809, Japan
[d] Global Station for Arctic Research, Global Institution for Collaborative Research and Education, Hokkaido University, Kita8, Nishi5, Kita-ku, Sapporo, 060-0808, Japan
[e] Slavic-Eurasian Research Center, Hokkaido University, Kita9, Nishi7, Sapporo, 060-0810, Japan
[f] Department of Earth and Planetary Sciences, Faculty of Science, Hokkaido University, Nishi8, Kita10, Sapporo, 060-0810, Japan
[g] Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido, 090-8507, Japan
[h] Disaster Prevention Research Institute, Kyoto University, 492-1 Fujinoi, Miyoshi, Tokushima, 778-0020, Japan
[i] Graduate School of Fisheries Science, Hokkaido University, 3-1-1 Minato-cho, Hakodate, 041-8611, Japan
[j] National Institute of Polar Research, 10-3 Midori-cho, Tachikawa, Tokyo, 190-8518, Japan
[k] Graduate School of Environmental Science, Hokkaido University, 20-5 Benten-cho, Hakodate, Hokkaido, 040-0051, Japan
[l] Atmosphere and Ocean Research Institute, University of Tokyo, 5-1-5 Kashiwanoha, Chiba, Japan
[m] Department of Ocean Sciences, Tokyo University of Marine Science and Technology, 4-5-7 Konan, Minato-ku, Tokyo, 108-8477, Japan
[n] Meteorological Research Institute, Japan Meteorological Agency, 1-1 Nagamine, Tsukuba, 305-0052, Japan
[o] Department of Anthropology and Archaeology, University of Calgary, 2500 University Drive N.W, Calgary, Alberta, T2N 1N4, Canada
[p] Instituto de Ciencias Físicas y Matemáticas, Universidad Austral de Chile, Valdivia, Chile
[q] Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, Hönggerbergring 26, 8093, Zurich, Switzerland
[r] Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057, Zurich, Switzerland
[s] Autonomous Systems Laboratory, ETH Zurich, Leonhardstrasse 21, 8092, Zurich, Switzerland
[t] Centre for Geo Genetics, University of Copenhagen, 1350, Copenhagen, Denmark
[u] B-431, 3971, Qaanaaq, Greenland

ARTICLE INFO

*Keywords:*
Greenland
Glacier
Ocean
Marine ecosystem
Natural hazard

ABSTRACT

Environments along the coast of Greenland are rapidly changing under the influence of a warming climate in the Arctic. To better understand the changes in the coastal environments, we performed researches in the Qaanaaq region in northwestern Greenland as a part of the ArCS (Arctic Challenge for Sustainability) Project. Mass loss of ice caps and marine-terminating outlet glaciers were quantified by field and satellite observations. Measurements and sampling in fjords revealed the important role of glacial meltwater discharge in marine ecosystems. Flooding of a glacial stream in Qaanaaq and landslides in a nearby settlement were investigated to identify the drivers of the incidents. Our study observed rapid changes in the coastal environments, and their critical impact on the society in Qaanaaq. We organized workshops with the residents to absorb local and indigenous knowledge, as well as to share the results and data obtained in the project. Continuous effort towards obtaining long-term

* Corresponding author. Arctic Research Center, Hokkaido University, Nishi11, Kita21, Sapporo, Hokkaido, 001-0021, Japan.
*E-mail address:* sugishin@lowtem.hokudai.ac.jp (S. Sugiyama).

https://doi.org/10.1016/j.polar.2020.100632
Received 30 March 2020; Received in revised form 16 December 2020; Accepted 17 December 2020
Available online 28 December 2020

observations requiring involvement of local communities is crucial to contribute to a sustainable future in Greenland.

## 1. Introduction

Greenland is characterized by the Greenland ice sheet and peripheral glaciers, which cover about 80% of the land area with a mean ice thickness of about 1700 m (Morlighem et al., 2017; Rastner et al., 2012; AMAP, 2017). The ice sheet and glaciers play a key role in the environment along the coast of Greenland as well as in the global climate system. For example, freshwater discharge from the ice sheet to the ocean is reported as approximately 1000 $km^3$ $a^{-1}$ (Bamber et al., 2012), which corresponds to ~25% of total river runoff into the Arctic Ocean (Haine et al., 2015). The discharge in the form of meltwater or icebergs affects coastal marine ecosystems, as well as the properties of seawater and ocean circulation. Moreover, glacial discharge carries substantial amounts of sediment and geochemical substances, thus additional impacts are expected in the ocean environment (e.g., Musilova et al., 2017; Overeem et al., 2017). Therefore, changes in the ice sheet and glaciers have a critical impact on the coastal environment in Greenland.

The Greenland ice sheet and glaciers are losing mass under the rapidly changing climate in the Arctic. Ice mass loss in Greenland began in 1980–90s, and greatly accelerated in the 21st century (e.g. Mouginot et al., 2019; van den Broeke et al., 2016). The rate of the mass loss changed from −40 Gt $a^{-1}$ in 1990–2000 to −185 Gt $a^{-1}$ 2000–2010, and further accelerated to −286 Gt $a^{-1}$ in 2010–2019 (Mouginot et al., 2019). The loss of ice from Greenland accounts for nearly half of the sea level rise caused by glaciers and ice sheets in 2004–2010 (AMAP, 2017). One of the mechanisms of the mass loss observed in Greenland is increasingly negative surface mass balance affected by intensive summer melting. Rising temperatures in the Arctic are the most important driver of the melt increase. Melt is also affected by albedo reduction due to expanding bare ice area, darkening ice surface, and snow grain growth (e.g. Box et al., 2012; Tedesco et al., 2016; Ryan et al., 2019). Another important mechanism of the mass loss is acceleration of marine-terminating glaciers. Satellite observations have shown rapid changes of the glaciers near the calving front, where ice discharge increases, thickness decreases and the front position retreats (e.g. Joughin et al., 2004; Rignot and Kanagaratnam, 2006; Howat et al., 2007). Warming oceans are suspected as drivers of the glacier change, but our understanding of the processes connecting the ocean with glacier change are insufficient (e.g., Rignot et al., 2010; Straneo and Heimbach, 2013; Straneo et al., 2019).

An increasing body of evidence, reported by recent studies, demonstrates the importance of glacial discharge in the coastal marine environment around Greenland. Glaciers discharge a large amount of suspended sediment into the ocean (Overeem et al., 2017), which carries bioavailable iron required for primary production in the ocean (Bhatia et al., 2013). Subglacial discharge from marine-terminating glaciers upwells in fjords, where nutrient-rich deep ocean water is transported to the surface (Meire et al., 2017; Cape et al., 2018; Hopwood et al., 2018). Further, glacier surface meltwater is a significant source of dissolved organic carbon, which is produced by microbial communities on the ice surface (Musilova et al., 2017). Material transport caused by glacial discharge strongly affects biological activities in glacial fjords, as represented by the formation of foraging hot spots of seabirds and marine mammals in front of marine-terminating glaciers (Lydersen et al., 2014). Unique fjord ecosystems near the glacier front have been observed by residents for a long time, but scientific knowledge is insufficient to understand links connecting the glacial discharge, nutrient transport, primary production, fish, birds, and marine mammals.

In 2011, we launched a research project in Qaanaaq, northwestern Greenland (Fig. 1), under the framework of a Japanese interdisciplinary Arctic research project, GRENE (Green Network of Excellence) Arctic Climate Change Research Project. The objective of the study was to quantify the mass loss of glaciers and the ice sheet in the Qaanaaq region, and better understand the mechanism driving the ice loss. Soon after the first field activity in 2012, we realized the importance of the ocean in the observed glacial changes, as well as the influence of glacial discharge on the ocean environment. Thus, we have expanded our research area to include the ocean, and chosen glacier-ocean interaction as the central research subject of the next project ArCS (Arctic Challenge for Sustainability) began in 2015 (Fig. 2). In the ArCS Project, we further expanded our research to include the impact of changing coastal environments on society in Qaanaaq. This is because serious impacts on society were clearly observed as a result of natural disasters in the form of landslides and glacial flooding.

In this contribution, we summarize our research activities in the Qaanaaq region and review important findings obtained under the ArCS Project. Studies described in this paper are contributions to ArCS Project Theme 2 "Variations in the ice sheet, glaciers, ocean and environment in the Greenland region". A paper by Goto-Azuma et al. (2020) describes another part of the Theme 2 activities, which studied variability of the Greenland ice sheet and climate using ice cores and snow samples from interiors of the ice sheet.

## 2. Study site

Qaanaaq (77°28′ N, 69°14′ W) is a settlement in northwestern Greenland of approximately 600 people (Fig. 1). We initiated our research project in this region because of its proximity to Qaanaaq Airport that facilitates logistics, previous and ongoing Japanese research activities based in Qaanaaq (e.g., Matoba et al., 2002; Uetake et al., 2010; Aoki et al., 2014), and the sparsity of glacier studies despite recently accelerated mass loss in northwestern sector of the Greenland ice sheet (Khan et al., 2010). The village is located on the coast of a peninsula, which is mostly covered by Qaanaaq Ice Cap (260 $km^2$) (Fig. 1). The ocean in front of the village is a part of Inglefield Bredning, which at ~100 km long and ~20 km wide is the largest fjord system in the region (Fig. 1). The ocean is covered by sea ice over winter and

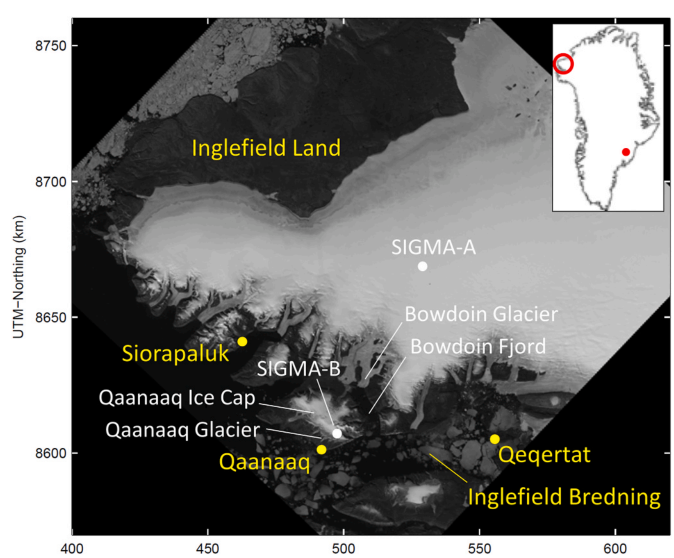


**Fig. 1.** Satellite image (Landsat 7 on July 24, 1999) of the Qaanaaq region in northwestern Greenland. The inset shows the locations of Qaanaaq (○) and the SE-Dome drilling site (●) in Greenland.

spring until it opens generally in early July. The condition of sea ice is of great concern to the local community because it enables people to use dog sledges and snowmobiles. The timing of sea ice opening is of great interest to the residents because the first supply ship of the year arrives as soon as the sea ice disappears. Because a number of marine-terminating glaciers feed the fjord, icebergs are abundant near the settlement. They are utilized as a freshwater resource in winter time.

## 3. Study results

### 3.1. Mass loss of ice caps and outlet glaciers

Recent mass loss of the ice sheet in northwestern Greenland has been reported by previous studies (Khan et al., 2010; Kjær et al., 2012). However, details of the changes were unclear because research in northwestern Greenland was sparse. To quantify ice loss and its variations in space and time, we performed satellite and field observations on ice caps and outlet glaciers in the Qaanaaq region.

We generated digital elevation models (DEMs) from satellite images to measure surface elevation change on six ice caps in the study area. This study revealed thinning of the ice caps from 2006 to 2010 at a rate of $-1.1$ m a$^{-1}$ (Saito et al., 2016). Comparison with a previous study indicated a two-fold increase in the thinning rate from 2003 to 2008 (Bolch et al., 2013). The most important driver of the mass loss is atmospheric warming, which is represented by a summer temperature increase in Qaanaaq at a rate of 0.12 °C a$^{-1}$ during 1997–2013 (Saito et al., 2016). In addition to the warming trend, melt is enhanced by albedo reduction due to glacial microbes covering ice surfaces (Sugiyama et al., 2014; Takeuchi et al., 2018). The abundance of the microbes is possibly affected by insoluble particles melting out from glacial ice (Matoba et al., 2020). Melt increase is also affecting the ocean because glacial discharge transports a greater amount of sediment into the ocean as demonstrated by our remote-sensing analysis (Ohashi et al., 2016).

Detailed in-situ measurements were carried out on Qaanaaq Glacier, an outlet glacier of Qaanaaq Ice Cap (Fig. 1). Surface mass balance of the ice cap has been measured from 2012 to present, and showed significantly large year-to-year variations (Tsutaki et al., 2017a; Kondo et al., 2019a). After a largely negative mass balance in the 2014/15 season ($-0.7$ m w.e. a$^{-1}$ as a mean over the glacier), slightly positive mass balance was observed in the years that followed: 2016/17 and 2017/18 (Fig. 3). Nevertheless, mass balance in 2018/19 was as negative as in 2014/15, and a generally negative mass balance trend is clearly observed. Our measurement is valuable because mass balance records are available at only a limited number of glaciers in Greenland's coastal areas (Machguth et al., 2016). We also performed in-situ measurements of ice surface elevation (Tsutaki et al., 2017b), ice speed and near-surface ice temperature (Tsutaki et al., 2017a) to understand the physical processes driving the glacier change. Ice temperature was elevated by latent heat released by refreezing meltwater, suggesting its influence on the dynamics of the glacier (Kondo et al., 2019a).

Studies were also carried out on the ice sheet's outlet glaciers. Satellite data showed that all 19 marine-terminating outlet glaciers in this region have been retreating since 2000 (Sakakibara and Sugiyama, 2018). Some of the glaciers retreated more rapidly than others, which were accompanied by acceleration near the glacier front. Presumably, retreat and thinning near the calving front triggered the acceleration, resulting in further mass loss as observed in other glaciers in Greenland (e.g. Joughin et al., 2004; Howat et al., 2007). DEM analyses demonstrated that greatest thinning rates were observed at rapidly retreating and speeding up glaciers (Fig. 4), which implied the critical role of ice dynamics in the mass loss of the outlet glaciers (Wang et al., submitted). Further analyses of satellite data revealed seasonal variations in ice speed controlled by meltwater production on the glaciers (Sakakibara and Sugiyama, 2020). This finding confirmed that the glacier dynamics are sensitive to external perturbation, which is modulated by climatic conditions.

The results obtained at outlet glaciers in the Qaanaaq region exemplified the importance of ice dynamics as well as surface mass balance to understand ice mass loss in Greenland. Accurate understanding of the driving mechanism of the glacier retreat, thinning and acceleration is critical to estimate the fate of the glaciers and its contribution to sea level rise. To this end, intensive research was performed at Bowdoin Glacier (official name after Bjørk et al. (2015) is Kangerluarsuup Sermia), one of the marine-terminating glaciers in the region.

### 3.2. Dynamics of a marine-terminating outlet glacier

Following the satellite-based study on the marine-terminating outlet glaciers, field measurements were carried out at Bowdoin Glacier located ~30 km northeast of Qaanaaq (Fig. 1). The glacier began a rapid retreat in 2008 after a relatively stable condition lasting for >20 years (Sugiyama et al., 2015). We have studied this glacier in collaboration with the Swiss Federal Institute of Technology in Zurich, including hot-water drilling through the glacier in July 2014 (Seguinot et al., 2020). Field campaigns were repeated in the summers of 2013–2017 and 2019.

An in-situ survey of the ice surface elevation showed thinning of the glacier in 2007–2013 at a rate faster than $-5$ m a$^{-1}$ (Tsutaki et al., 2016). Thinning was more rapid near the glacier front, and its magnitude was more than twice as large as the negative surface mass balance in the area. These observations implied that thinning was not simply due

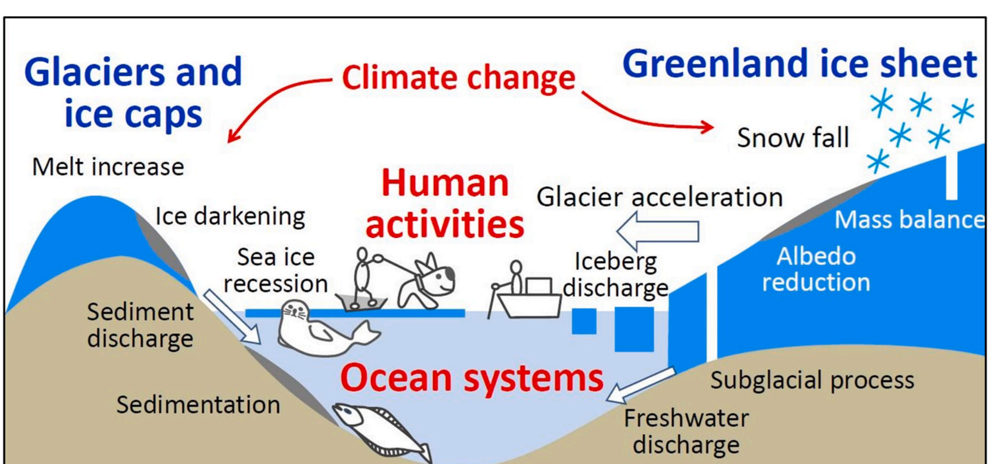


**Fig. 2.** Schematic diagram showing Greenland's coastal environments.

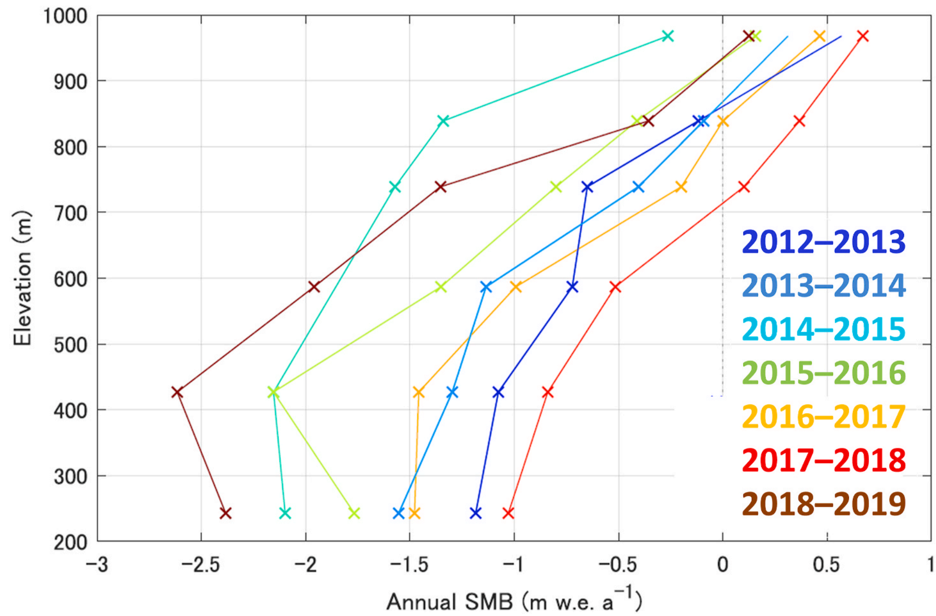


**Fig. 3.** Annual surface mass balance measured using stakes on Qaanaaq Ice Cap for the hydrological years from 2012/2013 to 2018/2019.

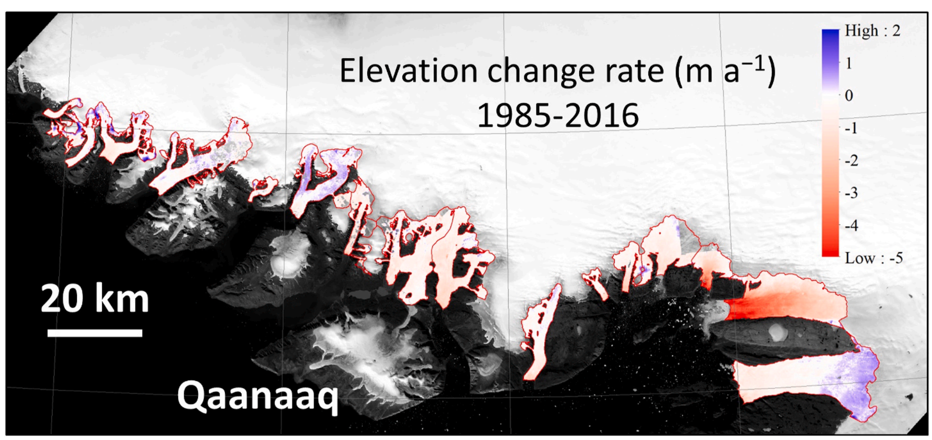


**Fig. 4.** Rates of surface elevation change from 1985 to 2016 on outlet glaciers in the Qaanaaq region. The measurement was performed by differencing DEMs derived from aerial photographs in 1985 (Korsgaard et al., 2016) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (Hirano et al., 2003) images in 2016.

to surface melting, but largely affected by ice flow acceleration, as observed by satellite data (Sakakibara and Sugiyama, 2018).

A possible driver of the retreat and acceleration of Bowdoin Glacier was the glacier bed geometry. We measured fjord depth near the glacier front, an area covered by ice before the recent retreat. Sonar measurements from a boat operated by a local collaborator in Qaanaaq, as well as from an unmanned research vessel (Yamasaki et al., 2017), revealed a bump on the ocean floor ~1 km from the front. The current glacier front is situated in an overdeepening area behind the bump, and the ice thickness was nearly equal to the isostatic equilibrium condition, i.e. gravitational force acting on the ice was counterbalanced by the buoyancy (Asaji et al., 2018). This observation strongly suggested the control of the fjord depth on the glacier front stability, a process proposed by numerical modelling studies (e.g. Nick et al., 2009).

To improve our understanding of physical processes controlling the recent retreat of Bowdoin Glacier, intensive field measurements have been carried out near the ice front. In-situ measurements near the front of a calving glacier are particularly important, but such measurements are sparse because the ice surface is crevassed and the front is unstable. Several different types of unmanned aerial vehicles (UAVs) were operated on the glacier in the summers of 2015–2017 and in 2019 to map repetitively the calving front by photogrammetry for analyzing ice motion and calving events. Detailed analyses of the resulting orthoimages show that spatial ice speed variations control the location and direction of a crack formation, and lead to large-scale calving (Jouvet et al., 2017). The ice speed field was affected by a subglacial bump near the glacier front, thus bed geometry is an important control of the magnitude and frequency of calving events. The images taken by the UAVs were also utilized to investigate tsunami waves generated by calving. This study demonstrated that tsunami measurement is a promising tool for a long-term monitoring of calving activity (Minowa et al., 2019). Further, the UAV images captured turbid water upwelling from the glacier bed, i.e. a meltwater plume in front of the glacier (Jouvet et al., 2018). The plume formation plays a critical role not only for submarine ice melting (e.g., Motyka et al., 2003; Rignot et al., 2010), but also for glacial fjord ecosystems, which will be described in the next subsection. Glacier dynamics were studied by means of seismic measurements as well, which revealed semidiurnal seismicity variations driven by tidal ice speed variations (Podolskiy et al., 2016). The glacier flows faster during low tide, which stretches ice and causes more frequent icequakes due to crevasse opening. A terrestrial radar interferometer revealed that a large crevasse widened at the fastest rate during low tide and lead to a major calving event in 2017 (van Dongen et al., 2020). Repeated measurements in 2019 suggested the calving mechanism of Bowdoin Glacier is changing in recent years under the influence of ice thinning near the front (van Dongen et al., in press).

Motivated by these in-situ observations, full-Stokes three-dimensional numerical models were developed to study the dynamics of Bowdoin Glacier. Basal friction was optimized using an inverse method, so that regions of enhanced basal drag were identified and observed short-term ice speed variations, including the tidal modulation, were partially reproduced (Seddik et al., 2019). The numerical experiment implied the importance of subglacial water pressure, demonstrating the need for studies on surface meltwater drainage to the glacier bed (Podolskiy, 2020). Higher resolution models were applied to the calving front to investigate calving events captured by UAV measurements (Jouvet et al., 2017; van Dongen et al., 2020). These studies highlighted the importance of surface meltwater, tide and submarine ice geometry for crevasse opening leading to large calving. Numerical modelling of calving glacier fronts based on in-situ data is still sparse, thus these numerical experiments on Bowdoin Glacier provided new insights into the dynamics and calving processes of a marine-terminating glacier.

### 3.3. Influence of glacial meltwater on fjord environments

Near the front of Bowdoin Glacier, numerous seabirds were observed particularly in the vicinity of meltwater plumes. Although such foraging hotspots have been recognized by local hunters, processes maintaining this unique ecosystem were unclear. Moreover, only a few ocean measurements have been reported in the Qaanaaq region (Dybkjær et al., 2011; Willis et al., 2018). To investigate a link between glacial discharge and physical/biogeochemical environments of fjords, we carried out ocean measurements in the 2014–2019 summer seasons using small boats operated by local collaborators in Qaanaaq.

Temperature and salinity measurements in Bowdoin Fjord (Fig. 1) showed a water structure similar to those observed in other Greenlandic fjords (e.g. Straneo and Heimbach, 2013). Relatively warm and salty Atlantic Water occupied depths deeper than 200 m, which was overlain by cold and relatively fresh Polar Water (Ohashi et al., 2020). Numerical model experiments showed an interaction between subglacial meltwater discharge and fjord stratification. The amount of discharge affects water properties and stratifications in the fjord, whereas annual variabilities in the stratification control distribution of the meltwater discharge into the fjord (Matsumura et al., 2017; Ohashi et al., 2020). Seasonal variations in the water properties were investigated by deploying mooring devices in the fjord from 2016 to 2019. Measurements 17 km from the glacier showed relatively small seasonal temperature variations, whereas bottom water 1 km from the glacier indicated significant cooling during the summer periods (Fujishi et al., 2019).

Intensive measurements and sampling in Bowdoin Fjord revealed a link between meltwater discharge and glacial fjord ecosystems (Fig. 5). When subglacial discharge upwells along the glacier front, nutrient rich deep water is entrained into the upwelling meltwater (Kanna et al., 2018). The concentrations of macronutrients and dissolved inorganic carbon in the upwelling water were several times greater than those sampled in the fjord. Thus, meltwater discharge transports nutrients to a near-surface layer, where the nutrients are used for plankton blooms. Since subglacial meltwater is rich in iron, the upwelling discharge also enhances iron concentration in the fjord and facilitate summer plankton boom (Kanna et al., 2020). Moreover, meltwater upwells with large-sized zooplankton, which is important prey for fish and seabirds aggregating in the plume area (Naito et al., 2019; Matsuno et al., 2020). Interestingly, subglacial discharge affects seabird habitat, depending on foraging behavior of species (Nishizawa et al., 2019). Surface feeders aggregate near the glacier front because abundant zooplankton and fish are available. In contrast, divers keep away from the glacier front and forage outside the fjord, since turbid glacial discharge hinders birds from diving. Further, underwater acoustic measurements in Bowdoin Fjord indicated the presence of narwhals within several hundred meters of the calving front of Bowdoin Glacier (Podolskiy and Sugiyama, 2020). This result suggests that there could be some poorly known influence of glacial discharge on narwhals, an endemic species in the Arctic and an important resource for indigenous people in northwestern Greenland. Our observations indicated the critical importance of glacial discharge in the fjord ecosystem. Therefore, serious impacts on the marine productivity are expected in the case of changes in the amount of meltwater discharge or the glacier front position.

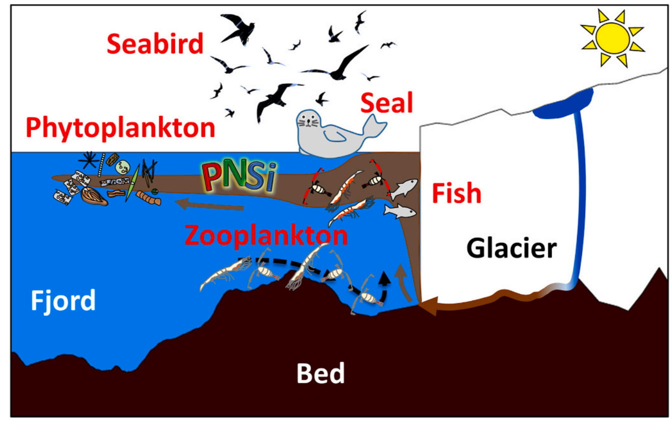


**Fig. 5.** Schematic diagram showing a glacial meltwater plume in front of a marine terminating glacier and fjord ecosystems. Subglacial discharge upwells with macronutrients (nitrate, phosphate and silicate), which facilitates phytoplankton bloom. Upwelling water also transports zooplankton to the surface, forming foraging hot spots of seabirds and marine mammals.

### 3.4. Sea ice, snow and atmospheric conditions

Ice cores and snow samples were collected and analyzed to investigate atmospheric conditions in Greenland. A 60-m-long ice core was drilled at SIGMA-A, located in the accumulation area of the ice sheet at 70 km northeast from Qaanaaq (78° 03′ N, 67° 38′ W, 1490 m a.s.l.) (Fig. 1). The site is located in the so-called percolation zone (Benson, 1961), where the magnitude of summer melt is affected by recent warming trends. During a record surface melt event in 2012 (Nghiem et al., 2012), for example, a remarkable amount of snowmelt and continuous heavy rainfall (100 mm in four-day period) were observed at the site (Niwano et al., 2015). The melt feature fraction of the ice core showed a significant increase in snow melt over the last ten years (Matoba et al., 2018). Water stable isotopes and chemical impurities of snow and ice samples were analyzed to identify the source of water to the region and reconstruct the history of sea ice concentration in Baffin Bay (Kurosaki et al., 2018, 2020). Another ice core drilled in southeastern Greenland at SE-Dome (67° 11′ N, 36° 22′ W, 3170 m a.s.l.) (Fig. 1) was analyzed for material transport to Greenland from other regions in the Northern Hemisphere. The results indicated that ice in Greenland preserves tracers of biomass burning events in eastern Canada (Parvin et al., 2018), and documents anthropogenic nitrate emission from North America (Furukawa et al., 2017; Iizuka et al., 2018).

Sea ice conditions in the Qaanaaq region were studied based on field and satellite observations. UAV measurements in Qaanaaq and field data obtained since 2013 in Siorapaluk, a settlement located 50 km northwest from Qaanaaq, were utilized to improve an algorithm to obtain sea ice thickness from microwave satellite data. Improved algorithms contributed to accurate mapping of sea ice thickness over the Arctic Ocean, and also to that in the Southern Ocean (Hoshino et al., 2018; Tateyama et al., 2018).

Meteorological conditions in the study area are monitored by automatic weather stations on the ice sheet at SIGMA-A and on Qaanaaq Ice Cap (SIGMA-B, 77°31′ N, 69°04 W, 944 m a.s.l.) (Fig. 1) (Aoki et al., 2014). These stations were installed in summer 2012 and have been continuously operated as stations of the Global Cryosphere Watch network of surface measurement. This station provides an important data set because long-term meteorological observation in northwestern Greenland is sparse. The meteorological data are utilized for various studies in the region, including regional climate modelling, surface mass balance and glacial discharge investigations (Niwano et al., 2015, 2018; Tsutaki et al., 2017a; Kondo et al., 2019b, submitted). The data obtained is provided through the Arctic Data Archiving System established and maintained under the GRENE and ArCS Projects.

### 3.5. *Social dimension of the climate change*

Rapidly changing coastal environments affect society in Greenland. In collaboration with social scientists and residents in Qaanaaq, we extended our study from natural environments to the social dimension. Based on anthropological research activities in Qaanaaq and Siorapaluk, Hayashi and Walls (2019) proposed a framework to understand the complex relationship between environmental changes and dynamic social response processes. Development of non-living resources in Greenland is often taken as a one-way impact on the indigenous people from an outside society. Takahashi (2020) discussed the initiative of local communities in the resource development, by taking into consideration political studies on the self-rule government of Greenland.

Direct impacts of environmental changes on society have been clearly observed in Qaanaaq. On 21 July in 2015, an outlet stream of Qaanaaq Glacier flooded and destroyed a road connecting the settlement and Qaanaaq Airport. The stream flooded again in the following year on August 2, 2016, causing even greater destruction to the road. Bridges in the settlement were also destroyed by increased discharge. To investigate the details of the floods in 2015 and 2016, we measured discharge of the outlet stream and melt on the glacier in 2017–2019. Together with meteorological data from SIGMA-B, our study confirmed that the flood in 2015 was caused by intensive snow and ice melting on the glacier, whereas that in 2016 was due to a heavy rain event (Kondo et al., 2019b, submitted). Accurate quantification of glacial discharge from a relatively small basin is still difficult for state-of-the-art climate models (Mankoff et al., 2020), thus discharge measurement and local scale modelling are crucial to understand the flood mechanism and estimate a risk in the future. The rain event in 2016 caused another disaster in Siorapaluk. Rainwater triggered landslides on a steep slope behind the settlement, and several buildings were damaged by debris and flush floods (Yamasaki and Watanabe, 2019; Walls et al., 2020). Analysis of the landslide deposit suggested that unstable shattered basal rocks slid down the steep slope. These incidents indicate the urgent need to investigate these hazards and prepare further actions for disaster prevention.

## 4. Community involvement

Our field research activity was supported by local collaborators in Qaanaaq. Particularly, ocean measurements were possible only through collaborations with hunters, who are familiar with local environments and skillful at boat operation in the icy fjords. The collaborators showed interest in our measurements, and provided useful knowledge and suggestions for our study. For example, the hunters were interested in our fjord depth measurements because water depth is a key of information for catching halibut, an important fishery resource in Qaanaaq. Based on their knowledge of fjord depths, we were able to plan efficient and safe measurement routes.

Following a suggestion by one of the collaborators, we organized the first workshop with the residents on July 25, 2016 at a gymnasium in Qaanaaq (Fig. 6a). We introduced our research project and explained study results. The audience actively questioned and commented on our activities. Because of their interests and requests, ocean depth data were compiled into bathymetry maps and distributed to the audience in the following workshop held on 30 July 2017. A hazard map was generated to illustrate the risk of landslides in Siorapaluk and distributed to the residents in 2019 (Fig. 7). The workshop in Qaanaaq was repeated every summer and also held in the smaller settlement of Qeqertat, located 60


**Fig. 6.** (a) Workshop held in Qaanaaq on July 25, 2016 and (b) Qeqertat on August 18, 2019. (c) Oral session and (d) booth presentation in Greenland Science Week in Nuuk on December 5, 2019.

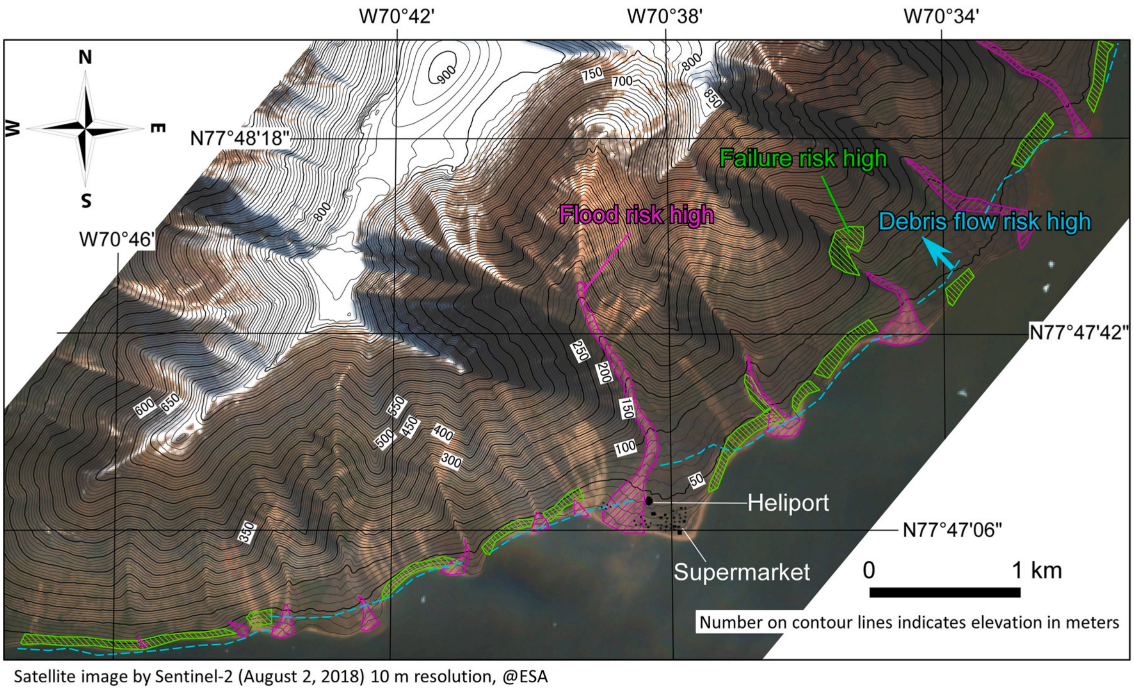


**Fig. 7.** Map of Siorapaluk showing a risk of landslide hazard. Green and purple shades indicate high risk areas of slope failure and flood, respectively. The map is part of materials distributed in the workshop in Qaanaaq on August 8, 2019 and presented in Greenland Science Week in Nuuk on December 5, 2019.

km east (Figs. 1 and 6b). Audience comments provided a wealth of local and indigenous knowledge, which accurately capture phenomena in natural environments. For example, hunters recognize tidal influence on the frequency of calving events, which is consistent with our ice speed and seismicity measurements on Bowdoin Glacier. To better understand the perspective of the community on recent climate change, we provided a questionnaire to survey the workshop audience and other residents (Sugiyama, 2020). The workshops provided us with an important opportunity to provide information to the Qaanaaq community detailing our research activity. We also shared study results and data, exchanged ideas about climate change and its social impact, and discussed future subjects of study.

To extend our effort towards community involvement, we organized an oral session and booth presentation at Greenland Science Week held in December 2019 in the capital of Greenland, Nuuk. This international symposium aimed to build bridges between science and the Greenlandic society, and create a collaboration platform for the Greenlandic and international science communities. In one of the sessions, together with a local collaborator, we introduced research activities and collaborations with the community in Qaanaaq (Fig. 6c). A social scientist from the Greenland Institute of Natural Resources commented on our presentations and acted as a moderator to the audience. At our booth, we presented posters and videos, displayed scientific instruments, and performed a model experiment of a glacial meltwater plume (Fig. 6d). The presentations were favorably received by the symposium participants, who included researchers, government officers, citizens, school teachers and students. It was one of the emphases of the symposium that local community should be informed of a scientific project, involved in research activity, and incorporated in project design.

## 5. Conclusion

This paper summarized the studies on ice sheet/glacier-ocean interaction in northwestern Greenland, which were carried out as part of ArCS Project Theme 2. Following studies focused on the Greenland ice sheet, glaciers and ice caps in the GRENE Project from 2011, we extended our research area to the ocean and coastal environments in the Qaanaaq region. The influence of the changing coastal environments on human society was investigated as well. We focused efforts of a broad range of researchers on the specific region, so that diverse research questions were tackled through multidisciplinary approaches.

The study indicated retreat and thinning of all marine-terminating outlet glaciers in the region. Rapid retreat and thinning were accompanied by ice speed acceleration, implying a critical role of ice dynamics in the recent glacier change. Intensive field measurements near the calving front of Bowdoin Glacier revealed a critical influence of bed geometry on the retreat and acceleration. New findings were also obtained for mechanisms of calving and ice motion. Monitoring on Qaanaaq Ice Cap since 2012 has shown large annual variations in the surface mass balance, which demonstrated the importance of a long-term in-situ observation.

Ocean measurements were performed in Bowdoin Fjord and Inglefield Bredning to understand the role of glacial meltwater in fjord ecosystems. Upwelling of subglacial discharge transports nutrients and plankton from deep water to the fjord surface. We quantified the nutrient transport and identified the upwelling plume as the key to maintaining feeding hotspots of sea birds and marine mammals near the glacier front. Seabird and plankton habitat were controlled by the upwelling plume, thus changes in the marine-terminating glaciers have a potential impact on the marine ecosystems. Further effort is needed to accurately understand the impact of glacier changes on important marine resources, fish and marine mammals.

Together with research on sea ice, ice cores and meteorological conditions, our data indicated rapid changes in the coastal environments in the Qaanaaq region. Such changes pose serious impact on societies along the coast of Greenland. We investigated flooding of an outlet stream of Qaanaaq Glacier, which destroyed infrastructure in 2015 and 2016. Our study identified glacier melting and heavy rain as the causes of the floods, suggesting an increase in flood risk under warming climate. Rain events were also responsible for landslides at Siorapaluk. Involvement of a broader range of researchers, e.g. climatologists, engineers and social scientists, is required for mitigation and hazard prevention in the future.

Study results and data obtained in the project were shared with the community, by organizing workshops with local collaborators in Qaanaaq and Qeqertat. We also reported our activity in a symposium held in Nuuk in 2019. The collaborations and conversations with residents allowed us to identify relevant future research directions. Designing a research project with involvement of a community is crucial to better contribute to a sustainable future in Greenland and other regions in the Arctic.

## 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.

## Acknowledgement

The authors thank GRENE and ArCS Greenland project members for their contributions in Qaanaaq. Kim Petersen and Sakiko Daorana provided assistance with field activities and workshops in Qaanaaq. Lene Kielsen Holm contributed to the session as part of Greenland Science Week 2019. David Qujaukeitsoq, Ilannguaq Karlsen and Pivinnguaq Morch acted as translators in the workshops. We thank Kumiko Goto-Azuma for handling the ArCS Theme 2 activity as the principal investigator. This study was funded by the Japanese Ministry of Education, Culture, Sports, Science and Technology through the GRENE Arctic Climate Research Project, ArCS (Arctic Challenge for Sustainability) (Program Grant Number JPMXD1300000000) and ArCS II Projects (JPMXD1420318865). The study was partially supported by Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number JP16H02224. The research on Bowdoin Glacier was supported by Swiss National Science Foundation through the project "Dynamic changes of tidewater outlet glaciers: Bowdoin glacier, Northwest Greenland" (SNSF Grant 200020_169558).

## References

AMAP, 2017. Snow, water, ice and permafrost in the arctic (SWIPA) 2017. In: Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. Xiv + 269, ISBN 978-82-7971-101-8.

Aoki, T., Matoba, S., Uetake, J., Takeuchi, N., Motoyama, H., 2014. Field activities of the "snow impurity and glacial microbe effects on abrupt warming in the arctic" (SIGMA) project in Greenland in 2011–2013. Bull. Glaciol. Res. 32, 3–20. https://doi.org/10.5331/bgr.32.3.

Asaji, I., Sakakibara, D., Sugiyama, S., Yamasaki, S., 2018. Influence of ocean bed geometry on the front variations of Bowdoin Glacier, northwestern Greenland. In: Annual Report on Snow and Ice Studies in Hokkaido, vol. 37, pp. 119–122.

Bamber, J., Van Den Broeke, M., Ettema, J., Lenaerts, J., Rignot, E., 2012. Recent large increases in freshwater fluxes from Greenland into the North Atlantic. Geophys. Res. Lett. 39 (19), 8–11. https://doi.org/10.1029/2012GL052552.

Benson, C.S., 1961. Stratigraphic studies in the snow and firn of the Greenland ice sheet. Folio Geographica Danica 9, 13–37.

Bhatia, M.P., Kujawinski, E.B., Das, S.B., Breier, C.F., Henderson, P.B., Charette, M.A., 2013. Greenland meltwater as a significant and potentially bioavailable source of iron to the ocean. Nat. Geosci. 6 (4), 274–278. https://doi.org/10.1038/ngeo1746.

Bjørk, A.A., Kruse, L.M., Michaelsen, P.B., 2015. Getting Greenland's glaciers right – a new data set of all official Greenlandic glacier names. Cryosphere 9, 2215–2218. https://doi.org/10.5194/tc-9-2215-2015.

Bolch, T., Sandberg Sørensen, L., Simonsen, S.B., Mölg, N., Machguth, H., Rastner, P., Paul, F., 2013. Mass loss of Greenland's glaciers and ice caps 2003–2008 revealed from ICESat laser altimetry data. Geophys. Res. Lett. 40 (5), 875–881. https://doi.org/10.1002/grl.50270.

Box, J.E., Fettweis, X., Stroeve, J.C., Tedesco, M., Hall, D.K., Steffen, K., 2012. Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. Cryosphere 6 (4), 821–839. https://doi.org/10.5194/tc-6-821-2012.

Cape, M.R., Straneo, F., Beaird, N., Bundy, R.M., Charette, M.A., 2018. Nutrient release to oceans from buoyancy-driven upwelling at Greenland tidewater glaciers. Nat. Geosci. 12, 34–39. https://doi.org/10.1038/s41561-018-0268-4.

Dybkjaer, G., Hoyer, J., Tonboe, R., Olsen, S., Rodwell, S., Wimmer, W., Sobjaerg, S., 2011. QASITEEX 2011, The Qaanaaq Sea Ice Thermal Emission Experiment, Field and Data Report. Danish Meteorological Institute (DMI) Technical Report 11–18. DMI and Greenland Climate and Research Centre. ISSN:1399-1388.

Fujishi, Y., Fukamachi, Y., Kanna, N., Sugiyama, S., 2019. Long-term measurement of temperature, salinity and ocean current in the Bowdoin fjord in northwestern Greenland. Annual Report on Snow and Ice Studies in Hokkaido 38, 15–18.

Furukawa, R., Uemura, R., Fujita, K., Sjolte, J., Yoshimura, K., Matoba, S., Iizuka, Y., 2017. Seasonal-scale dating of a shallow ice core from Greenland using oxygen isotope matching between data and simulation. J. Geophys. Res.: Atmosphere 122 (10), 887. https://doi.org/10.1002/2017JD026716, 873–10.

Goto-Azuma, K., Homma, T., Saruya, T., Nakazawa, F., Komuro, Y., Nagatsuka, N., Hirabayashi, M., Kondo, Y., Koike, M., Aoki, T., Greve, R., Okuno, J., 2020. Studies on the variability of the Greenland ice sheet and climate. Polar Science. https://doi.org/10.1016/j.polar.2020.100557.

Haine, T.W.N., Curry, B., Gerdes, R., Hansen, E., Karcher, M., Lee, C., Rudels, B., Spreen, G., de Steur, L., Stewart, K.D., Woodgate, R., 2015. Arctic freshwater export: status, mechanisms, and prospects. Global Planet. Change 125, 13–35. https://doi.org/10.1016/j.gloplacha.2014.11.013.

Hayashi, N., Walls, M., 2019. Endogenous community development in Greenland: a perspective on creative transformation and the perception of future. Polar Science 21, 52–57. https://doi.org/10.1016/j.polar.2019.06.002.

Hirano, A., Welch, R., Lang, H., 2003. Mapping from ASTER stereo image data: DEMvalidation and accuracy assessment. ISPRS J. Photogrammetry Remote Sens. 57 (5), 356–370.

Hopwood, M.J., Carroll, D., Browning, T.J., Meire, L., Mortensen, J., Krisch, S., Achterberg, E.P., 2018. Non-linear response of summertime marine productivity to increased meltwater discharge around Greenland. Nat. Commun. 9 (1) https://doi.org/10.1038/s41467-018-05488-8.

Hoshino, S., Tateyama, K., 2018. Validation and evaluation of sea-ice thickness derived from satellite altimeter SIRAL in the Arctic. In: Proceedings of the 33rd International Symposium on Okhotsk Sea and Polar Oceans, pp. 43–46.

Howat, I.M., Joughin, I., Scambos, T.A., 2007. Rapid changes in ice discharge from Greenland outlet glaciers. Science 315 (5818), 1559–1561. https://doi.org/10.1126/science.1138478.

Iizuka, Y., Uemura, R., Fujita, K., Hattori, S., Seki, O., Miyamoto, C., Suzuki, T., Yoshida, N., Motoyama, H., Matoba, S., 2018. A 60 year record of atmospheric aerosol depositions preserved in a high-accumulation dome ice core, southeast Greenland. J. Geophys. Res.: Atmosphere 123, 574–589. https://doi.org/10.1002/2017JD026733.

Joughin, I., Abdalati, W., Fahnestock, M., 2004. Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier. Nature 432, 608–610. https://doi.org/10.1038/nature03130.

Jouvet, G., Weidmann, Y., Seguinot, J., Funk, M., Abe, T., Sakakibara, D., Seddik, H., Sugiyama, S., 2017. Initiation of a major calving event on the Bowdoin Glacier captured by UAV photogrammetry. Cryosphere 11, 911–921. https://doi.org/10.5194/tc-11-911-2017.

Jouvet, G., Weidmann, Y., Kneib, M., Detert, M., Seguinot, J., Sakakibara, D., Sugiyama, S., 2018. Short-lived ice speed-up and plume water flow captured by a VTOL UAV give insights into subglacial hydrological system of Bowdoin Glacier. Rem. Sens. Environ. 217, 389–399. https://doi.org/10.1016/j.rse.2018.08.027.

Khan, S.A., Wahr, J., Bevis, M., Velicogna, I., Kendrick, E., 2010. Spread of ice mass loss into northwest Greenland observed by GRACE and GPS. Geophys. Res. Lett. 37 (6), 1–5. https://doi.org/10.1029/2010GL042460.

Kjær, K.H., Khan, S.A., Korsgaard, N.J., Wahr, J., Bamber, J.L., Hurkmans, R., van den Broeke, M., Timm, L.H., Kjeldsen, K.K., Bjork, A.A., Larsen, N.K., Jorgensen, L.T., Faerch-Jensen, A., Willerslev, E., 2012. Aerial photographs reveal late-20th-century dynamic ice loss in northwestern Greenland. Science 337 (6094), 569–573. https://doi.org/10.1126/science.1220614.

Kanna, N., Sugiyama, S., Ohashi, Y., Sakakibara, D., Fukamachi, Y., Nomura, D., 2018. Upwelling of macronutrients and dissolved inorganic carbon by a subglacial freshwater driven plume in Bowdoin Fjord, northwestern Greenland. J. Geophys. Res.: Biogeosciences 123, 1666–1682. https://doi.org/10.1029/2017JG004248.

Kanna, N., Sugiyama, S., Fukamachi, Y., Nomura, D., Nishioka, J., 2020. Iron supply by subglacial discharge into a fjord near the front of a marine-terminating glacier in northwestern Greenland. Global Biogeochem. Cycles 34 (10), e2020GB006567. https://doi.org/10.1029/2020GB006567.

Kondo, K., Sakakibara, D., Tsutaki, S., Sugiyama, S., 2019a. Field measurements and numerical experiments on ice flow velocity of Qaanaaq Ice Cap, northwestern Greenland. Annual Report on Snow and Ice Studies in Hokkaido 38, 105–108.

Kondo, K., Sakakibara, D., Fukumoto, S., Sugiyama, S., 2019b. Meltwater discharge and flooding of the outlet stream of Qaanaaq Glacier, northwestern Greenland. Geophys. Res. Abstr. 21, EGU2019–11919.

Kondo, K., Sugiyama, S., Sakakibara, D., Fukumoto, S., Flood events caused by meltwater discharge from Qaanaaq Glacier, northwestern Greenland. J. Glaciol., (submitted).

Korsgaard, N.J., Nuth, C., Khan, S.A., Kjeldsen, K.K., Bjørk, A.A., Schomacker, A., Kjær, K.H., 2016. Digital elevation model and orthophotographs of Greenland based on aerialphotographs from 1978–1987. Scientific Data 3 (1), 160032.

Kurosaki, Y., Matoba, S., Iizuka, Y., Niwano, M., Tankawa, T., Aoki, T., 2018. Influence of environmental conditions near Baffin Bay on deuterium excess and chemical substances in falling snow in northwestern Greenland. Seppyo 80 (6), 515–529.

Kurosaki, Y., Matoba, S., Iizuka, Y., Niwano, M., Tankawa, T., Ando, T., Hori, A., Miyamoto, A., Fujita, S., Aoki, T., 2020. Reconstruction of sea ice concentration in northern Baffin Bay using deuterium excess in a coastal ice core from the northwestern Greenland Ice Sheet. J. Geophys. Res.: Atmosphere 125, e2019JD031668. https://doi.org/10.1029/2019JD031668.

Lydersen, C., Assmy, P., Falk-Petersen, S., Kohler, J., Kovacs, K.M., Reigstad, M., Steen, H., Strøm, H., Sundfjord, A., Varpe, Ø., Walczowski, W., Weslawski, J.M., Zajaczkowski, M., 2014. The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. J. Mar. Syst. 129, 452–471. https://doi.org/10.1016/j.jmarsys.2013.09.006.

Machguth, H., Thomsen, H.H., Weidick, A., Ahlstrøm, A.P., Abermann, J., Andersen, M. L., Andersen, S.B., Bjørk, A.A., Box, J.E., Braithwaite, R.J., Bøggild, C.E., Citterio, M., Clement, P., Colgan, W., Fausto, R.S., Gleie, K., Gubler, S., Hasholt, B., Hynek, B., Knudsen, N.T., Larsen, S.H., Mernild, S.H., Oerlemans, J., Oerter, H., Olesen, O.B., Smeets, C.J.P.P., Steffen, K., Stober, M., Sugiyama, S., Van As, D., Van Den Broeke, M.R., Van De Wal, R.S.W., 2016. Greenland surface mass-balance observations from the ice-sheet ablation area and local glaciers. J. Glaciol. 62 (235), 861–887. https://doi.org/10.1017/jog.2016.75.

Mankoff, K.D., Noel, B., Fettweis, X., Ahlstrom, A.P., Colgan, W., Kondo, K., Langley, K., Sugiyama, S., van As, D., Fausto, R.S., 2020. Greenland liquid water discharge from 1958 through 2019. Earth Syst. Sci. Data 12 (4), 2811–2841. https://doi.org/10.5194/essd-12-2811-2020.

Matoba, S., Yamazaki, T., Motoyama, H., 2002. Meteorological observation and chemical compositions of precipitation during the winter and spring season in 1997/98 at Siorapaluk, northwestern Greenland. Bull. Glaciol. Res. 19, 25–31.

Matoba, S., Niwano, M., Tanikawa, T., Iizuka, Y., Yamasaki, T., Kurosaki, Y., Aoki, T., Hashimoto, A., Hosaka, M., Sugiyama, S., 2018. Field activities at the SIGMA-A site, northwestern Greenland Ice Sheet, 2017. Bull. Glaciol. Res. 36, 15–22. https://doi.org/10.5331/bgr.18R01.

Matoba, S., Hazuki, R., Kurosaki, Y., Aoki, T., 2020. Spatial distribution of the input of insoluble particles into the surface of the Qaanaaq Glacier, northwestern Greenland. Front. Earth Sci. 8, 542557. https://doi.org/10.3389/feart.2020.542557.

Matsumura, Y., Ohashi, Y., Aoki, S., Sugiyama, S., 2017. Modeling subglacial meltwater plumes and associated sediment transport. Low Temp. Sci. 75, 77–84.

Matsuno, K., Kanna, N., Sugiyama, S., Yamaguchi, A., Yang, E.Y., 2020. Impacts of meltwater discharge from marine-terminating glaciers on the protist community in Inglefield Bredning, northwestern Greenland. Mar. Ecol. Prog. Ser. 642, 55–65. https://doi.org/10.3354/meps13324.

Meire, L., Mortensen, J., Meire, P., Juul-Pedersen, T., Sejr, M.K., Rysgaard, S., Nygaard, R., Huybrechts, P., Meysman, F.J.R., 2017. Marine-terminating glaciers sustain high productivity in Greenland fjords. Global Change Biol. 23 (12), 5344–5357. https://doi.org/10.1111/gcb.13801.

Minowa, M., Podolskiy, E.A., Jouvet, G., Weidmann, Y., Sakakibara, D., Tsutaki, S., Genco, R., Sugiyama, S., 2019. Calving flux estimation from tsunami waves. Earth Planet Sci. Lett. 515, 283–290. https://doi.org/10.1016/j.epsl.2019.03.023.

Morlighem, M., Williams, C.N., Rignot, E., An, L., Arndt, J.E., Bamber, J.L., Catania, G., Chauché, N., Dowdeswell, J.A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T.M., Kjeldsen, K.K., Millan, R., Mayer, L., Mouginot, J., Noël, B.P.Y., O'Cofaigh, C., Palmer, S., Rysgaard, S., Seroussi, H., Siegert, M.J., Slabon, P., Straneo, F., van den Broeke, M.R., Weinrebe, W., Wood, M., Zinglersen, K.B., 2017. BedMachine v3: complete bed topography and ocean bathymetry mapping of Greenland from multibeam. Geophys. Res. Lett. 44, 1–11. https://doi.org/10.1002/2017GL074954.

Motyka, R.J., Hunter, L., Echelmeyer, K.A., Connor, C., 2003. Submarine melting at the terminus of a temperate tidewater glacier, LeConte Glacier, Alaska, U.S.A. Ann. Glaciol. 36, 57–65. https://doi.org/10.3189/172756403781816374.

Mouginot, J., Rignot, E., Bjørk, A.A., van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B., Wood, M., 2019. Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. Proc. Natl. Acad. Sci. Unit. States Am. 116 (19), 9239–9244. https://doi.org/10.1073/pnas.1904242116.

Musilova, M., Tranter, M., Wadham, J., Telling, J., Tedstone, A., Anesio, A.M., 2017. Microbially driven export of labile organic carbon from the Greenland ice sheet. Nat. Geosci. 10 (5), 360–365. https://doi.org/10.1038/ngeo2920.

Naito, A., Abe, Y., Matsuno, K., Nishizawa, B., Kanna, N., Sugiyama, S., Yamaguchi, A., 2019. Surface zooplankton size and taxonomic composition in Bowdoin Fjord, north-western Greenland: A comparison of ZooScan, OPC and microscopic analyses. Polar Science 19, 120–129. https://doi.org/10.1016/j.polar.2019.01.001.

Nghiem, S.V., Hall, D.K., Mote, T.L., Tedesco, M., Albert, M.R., Keegan, K., Shuman, C.A., DiGirolamo, N.E., Neumann, G., 2012. The extreme melt across the Greenland ice sheet in 2012. Geophys. Res. Lett. 39, L20502 https://doi.org/10.1029/2012GL053611.

Nick, F.M., Vieli, A., Howat, I.M., Joughin, I., 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. Nat. Geosci. 2 (2), 110–114. https://doi.org/10.1038/ngeo394.

Nishizawa, B., Kanna, N., Abe, Y., Ohashi, Y., Sakakibara, D., Asaji, I., Sugiyama, S., Yamaguchi, A., Watanuki, Y., 2019. Contrasting assemblages of seabirds in the subglacial meltwater plume and oceanic water of Bowdoin Fjord, northwestern Greenland. ICES Journal of Marine Science fsz213. https://doi.org/10.1093/icesjms/fsz213.

Niwano, M., Aoki, T., Matoba, S., Yamaguchi, S., Tanikawa, T., Kuchiki, K., Motoyama, H., 2015. Numerical simulation of extreme snowmelt observed at the SIGMA-A site, northwest Greenland, during summer 2012. Cryosphere 9, 971–988. https://doi.org/10.5194/tc-9-971-2015.

Niwano, M., Aoki, T., Hashimoto, A., Matoba, S., Yamaguchi, S., Tanikawa, T., Fujita, K., Tsushima, A., Iizuka, Y., Shimada, R., Hori, M., 2018. NHM–SMAP: spatially and temporally high-resolution nonhydrostatic atmospheric model coupled with detailed snow process model for Greenland Ice Sheet. Cryosphere 12, 635–655. https://doi.org/10.5194/tc-12-635-2018.

Ohashi, Y., Iida, T., Sugiyama, S., Aoki, S., 2016. Spatial and temporal variations in high turbidity surface water off the Thule region, northwestern Greenland. Polar Science 10, 270–277. https://doi.org/10.1016/j.polar.2016.07.003.

Ohashi, Y., Aoki, S., Matsumura, Y., Sugiyama, S., Kanna, N., Sakakibara, D., 2020. Vertical distribution of water mass properties under the influence of subglacial discharge in Bowdoin Fjord, northwestern Greenland. Ocean Sci. 16, 545–564. https://doi.org/10.5194/os-16-545-2020.

Overeem, I., Hudson, B.D., Syvitski, J.P.M., Mikkelsen, A.B., Hasholt, B., Van Den Broeke, M.R., Noël, B.P.Y., Morlighem, M., 2017. Substantial export of suspended sediment to the global oceans from glacial erosion in Greenland. Nat. Geosci. 10 (11), 859–863. https://doi.org/10.1038/NGEO3046.

Parvin, F., Seki, O., Fujita, K., Iizuka, Y., Matoba, S., Ando, T., Sawada, K., 2018. Assessment for paleoclimatic utility of biomass burning tracers in SE-Dome ice core, Greenland. Atmos. Environ. 196, 86–94. https://doi.org/10.1016/j.atmosenv.2018.10.012.

Podolskiy, J., 2020. Toward the acoustic detection of two-phase flow patterns and Helmholtz resonators in englacial drainage systems. Geophys. Res. Lett. 47 (6), e2020GL086951 https://doi.org/10.1029/2020GL086951.

Podolskiy, E.A., Sugiyama, S., Funk, M., Walter, F., Genco, R., Tsutaki, S., Minowa, M., Ripepe, M., 2016. Tide-modulated ice flow variations drive seismicity near the calving front of Bowdoin Glacier, Greenland. Geophys. Res. Lett. 43, 2036–2044. https://doi.org/10.1002/2016GL067743.

Podolskiy, J., Sugiyama, S., 2020. Soundscape of a narwhal summering ground in a glacier fjord (Inglefield Bredning, Greenland). J. Geophys. Res.: Oceans 125, e2020JC016116. https://doi.org/10.1029/2020JC016116.

Rastner, P., Bolch, T., Mölg, N., Machguth, H., Le Bris, R., Paul, F., 2012. The first complete inventory of the local glaciers and ice caps on Greenland. Cryosphere 6 (6), 1483–1495. https://doi.org/10.5194/tc-6-1483-2012.

Rignot, E., Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland Ice Sheet. Science 311 (5763), 986–990. https://doi.org/10.1126/science.1121381.

Rignot, E., Koppes, M., Velicogna, I., 2010. Rapid submarine melting of the calving faces of West Greenland glaciers. Nat. Geosci. 3 (3), 187–191. https://doi.org/10.1038/ngeo765.

Ryan, J.C., Smith, L.C., As, D. Van, Cooley, S.W., Cooper, M.G., Pitcher, L.H., Hubbard, A., 2019. Greenland Ice Sheet surface melt amplified by snowline migration and bare ice exposure. Science Advances 5 (3), eaav3738. https://doi.org/10.1126/sciadv.aav3738.

Saito, J., Sugiyama, S., Tsutaki, S., Sawagaki, T., 2016. Surface elevation change on ice caps in the Qaanaaq region, northwestern Greenland. Polar Science 10 (3), 239–248. https://doi.org/10.1016/j.polar.2016.05.002.

Sakakibara, D., Sugiyama, S., 2018. Ice front and flow speed variations of marine-terminating outlet glaciers along the coast of Prudhoe Land, northwestern Greenland. J. Glaciol. 64 (244), 300–310. https://doi.org/10.1017/jog.2018.20.

Sakakibara, D., Sugiyama, S., 2020. Seasonal ice-speed variations in 10 marine-terminating outlet glaciers along the coast of Prudhoe Land, northwestern Greenland. J. Glaciol. 66 (255), 25–34. https://doi.org/10.1017/jog.2019.81.

Seddik, H., Greve, R., Sakakibara, D., Tsutaki, S., Minowa, M., Sugiyama, S., 2019. Response of the flow dynamics of Bowdoin Glacier, northwestern Greenland, to basal lubrication and tidal forcing. J. Glaciol. 65 (250), 225–238. https://doi.org/10.1017/jog.2018.106.

Seguinot, J., Funk, M., Bauder, A., Wyder, T., Senn, C., Sugiyama, S., 2020. Englacial Warming Indicates Deep Crevassing in Bowdoin Glacier, Greenland. Front. Earth Sci. 8, 65. https://doi.org/10.3389/feart.2020.00065.

Sugiyama, S., 2020. Through the Japanese field research in Greenland: A changing natural environment and its impact on human society. Polar Rec. 56, E8. https://doi.org/10.1017/S003224742000011X.

Sugiyama, S., Sakakibara, D., Matsuno, S., Yamaguchi, S., Matoba, S., Aoki, T., 2014. Initial field observations on Qaanaaq ice cap, northwestern Greenland. Ann. Glaciol. 55 (66), 25–33. https://doi.org/10.3189/2014AoG66A102.

Sugiyama, S., Sakakibara, D., Tsutaki, S., Maruyama, M., Sawagaki, T., 2015. Glacier dynamics near the calving front of Bowdoin Glacier, northwestern Greenland. J. Glaciol. 61 (226), 223–232. https://doi.org/10.3189/2015JoG14J127.

Straneo, F., Heimbach, P., 2013. North Atlantic warming and the retreat of Greenland's outlet glaciers. Nature 504 (7478), 36–43. https://doi.org/10.1038/nature12854.

Straneo, F., Sutherland, D.A., Stearns, L., Catania, G., Heimbach, P., Moons, T., Capes, M. R., Laidre, K.L., Barber, D., Rysgaard, S., Mottram, R., Olsen, S., Hopwood, M.J., Meire, L., 2019. The case for a sustained Greenland Ice Sheet-Ocean Observing System (GrIOOS). Frontiers in Marine Science 6, 138. https://doi.org/10.3389/fmars.2019.00138.

Takahashi, M., 2020. The contours of the development of non-living resources in Greenland. Polar Record: Special Issue: International Law for Sustainability in Arctic Resource Development. https://doi.org/10.1017/S0032247419000676.

Takeuchi, N., Sakaki, R., Uetake, J., Nagatsuka, N., Shimada, R., Niwano, M., Aoki, T., 2018. Temporal variations of cryoconite holes and cryoconite coverage on the ablation ice surface of Qaanaaq Glacier in northwest Greenland. Ann. Glaciol. 59 (77), 21–30. https://doi.org/10.1017/aog.2018.19.

Tateyama, K., Inoue, J., Hoshino, S., Sasaki, S., Tanaka, Y., 2018. Development of a new algorithm to estimate Arctic sea-ice thickness based on Advanced Microwave Scanning Radiometer 2 data. Okhotsk Sea and Polar Oceans Research 2, 13–18.

Tedesco, M., Doherty, S., Fettweis, X., Alexander, P., Jeyaratnam, J., Stroeve, J., 2016. The darkening of the Greenland ice sheet: Trends, drivers, and projections (1981-2100). Cryosphere 10 (2), 477–496. https://doi.org/10.5194/tc-10-477-2016.

Tsutaki, S., Sugiyama, S., Sakakibara, D., Sawagaki, T., 2016. Surface elevation changes during 2007–13 on Bowdoin and Tugto Glaciers, northwestern Greenland. J. Glaciol. 62 (236), 1083–1092. https://doi.org/10.1017/jog.2016.106.

Tsutaki, S., Sugiyama, S., Sakakibara, D., Aoki, T., Niwano, M., 2017a. Surface mass balance, ice velocity and near-surface ice temperature on Qaanaaq Ice Cap, northwestern Greenland, from 2012 to 2016. Ann. Glaciol. 59 (75), 181–192. https://doi.org/10.1017/aog.2017.7.

Tsutaki, S., Sugiyama, S., Sakakibara, D., 2017b. Surface elevations on Qaanaaq and Bowdoin Glaciers in northwestern Greenland as measured by a kinematic GPS survey from 2012–2016. Polar Data Journal 1, 1–16. https://doi.org/10.20575/00000001.

Uetake, J., Naganuma, T., Hebsgaardd, M.B., Kanda, H., Kohshima, S., 2010. Communities of algae and cyanobacteria on glaciers in west Greenland. Polar Science 4, 71–80.

van den Broeke, M.R., Enderlin, E.M., Howat, I.M., Kuipers Munneke, P., Noël, B.P.Y., van de Berg, W.J., van Meijgaard, E., Wouters, B., 2016. On the recent contribution of the Greenland ice sheet to sea level change. Cryosphere 10, 1933. https://doi.org/10.5194/tc-10-1933-2016.

van Dongen, E., Jouvet, G., Walter, A., Todd, J., Zwinger, T., Asaji, I., Sugiyama, S., Walter, F., Funk, M., 2020. Tides modulate crevasse opening prior to a major calving event at Bowdoin Glacier, Northwest Greenland. J. Glaciol. 66 (255), 113–123. https://doi.org/10.1017/jog.2019.89.

van Dongen, E.C.H., Jouvet, G., Sugiyama, S., Podolskiy, E.A., Funk, M., Benn, D.I., Lindner, F., Bauder, A., Seguinot, J., Leinss, S., Walter, F., in press. Thinning Leads to Calving-Style Changes at Bowdoin Glacier, Greenland, Cryosphere.

Walls, M., Hvidberg, M., Kleist, M., Knundsen, P., Mørch, P., Egede, P., Taylor, G., Phillips, N., Yamasaki, S., Watanabe, T., 2020. Hydrological instability and archaeological impact in Northwest Greenland: Sudden mass movement events signal new concerns for circumpolar archaeology. Quat. Sci. Rev. 248, 106600. https://doi.org/10.1016/j.quascirev.2020.106600.

Wang, Y., Sugiyama, S., Bjørk, A. A., Surface Elevation Change of Glaciers Along the Coast of Prudhoe Land, Northwestern Greenland from 1985 to 2018. J. Geophys. Res.: Earth Surface, (submitted).

Willis, J.K., Carroll, D., Fenty, I., Kohli, G., Khazendar, A., Rutherford, M., Trenholm, N., Morlighem, M., 2018. Ocean-ice interactions in Inglefield Gulf: Early results from NASA's Oceans Melting Greenland mission. Oceanography 31 (2), 100–108. https://doi.org/10.5670/oceanog.2018.211.

Yamasaki, S., Tabusa, T., Iwasaki, S., Hiramatsu, M., 2017. Acoustic water bottom investigation with a remotely operated watercraft survey system. Progress in Earth and Planetary Science 4, 25. https://doi.org/10.1186/s40645-017-0140-y.

Yamasaki, S., Watanabe, T., 2019. Landslide and flash flood caused by the 2016–17 heavy rain events in Siorapaluk, north Greenland. Geophys. Res. Abstr. 21. EGU2019-3516-2.