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# Recent ice mass loss in northwestern Greenland: Results of the GRENE Greenland project and overview of the ArCS project

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The Greenland ice sheet and peripheral ice caps are rapidly losing mass. This mass change has been captured by satellite remote sensing, but more detailed investigations are necessary to understand the spatiotemporal variations and mechanism of the ice loss. It has increased particularly in northwestern Greenland, but in-situ data for northern Greenland are generally sparse. To better understand the ice mass loss in northwestern Greenland, we studied the ice sheet, ice caps and calving glaciers in the Qaanaaq region, as a part of the Green Network of Excellence (GRENE) Arctic Climate Change Research Project. Field and satellite observations were performed to measure the mass loss of the ice caps and calving glaciers in the region. Detailed processes were investigated based on field measurements to understand mechanisms driving the ice loss. The field activities include mass balance monitoring on Qaanaaq Ice Cap since 2012, integrated field observations near the front of Bowdoin Glacier since 2013 and ocean measurements near the calving glaciers. In this contribution, we summarize the results of the GRENE Greenland project, and introduce an overview of the next project to be carried out under the framework of the Arctic Challenge for Sustainability Project (ArCS).

**Keywords:** Greenland, glacier, ice sheet, ice cap, ice-ocean interaction

## 1. Introduction

The surface area of Greenland is  $\sim 80\%$  covered by ice with a mean ice thickness of 1.7 km. Change in this ice mass is of great importance to the global environment because melting of the entire Greenland ice sheet would cause mean sea level to rise by 7.36 m (Bamber et

al., 2013). Recent studies based on satellite remote sensing and regional climate models have shown that ice in Greenland has decreased rapidly over the last few decades (e.g. van den Broeke et al., 2009; Velicogna, 2009; Rignot et al., 2011). The mass change of the Greenland ice sheet, the second largest land ice on Earth, is reported as  $-229 \pm 60 \text{ Gt a}^{-1}$ , which is equivalent to the

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sea level rise of  $0.63 \text{ mm a}^{-1}$  (IPCC, 2013). Changes are occurring also at peripheral ice caps and glaciers physically separated from the ice sheet, which account for  $\sim 7\%$  of the ice-covered area in Greenland (Rastner et al., 2012). They have lost ice at a rate of  $41 \pm 17 \text{ Gt a}^{-1}$  from 2003 to 2008, contributing to sea level rise of  $0.12 \text{ mm a}^{-1}$  (Bolch et al., 2013). A number of studies have shown acceleration of the ice loss in Greenland since the 1990s, and thus accurate quantification is crucial to predict future sea level change.

These changes are non-uniformly distributed over Greenland. Rapid mass loss has been observed particularly in the coastal regions because snow and ice melt is increasing in lower-elevation areas and calving glaciers are discharging increasing amount of ice into the ocean. These are the two main drivers of the ongoing mass loss of the ice sheet, and ice caps are thinning primarily because of increasingly negative surface mass balance driven by the increasing snow and ice melt at lower elevations (Mernild et al., 2011; Rinne et al., 2011). Snow and ice are melting over a broader area and for a longer period under the influence of enhanced atmospheric warming in the Arctic. As a result of melting, the grain size of snow increases, ice surface areas reach higher elevations and the spatial coverage of light-absorbing glacial microbes increases (e.g. Wientjes and Oerlemans, 2010). These processes contribute to albedo reduction and further enhance melting. Near the front of calving glaciers, acceleration, thinning and retreat have been reported since the beginning of the 21st century. These changes were first discovered at large glaciers in southeastern and western regions (e.g. Joughin et al., 2004; Howat et al., 2005), but were later observed at other glaciers around the ice sheet (e.g. Rignot et al., 2006; Moon et al., 2012). Mechanisms of the glacier changes are not fully understood, but glacier and fjord bed geometry is suggested as a key driver of acceleration and rapid retreat (e.g. Nick et al., 2009). Moreover, subaqueous melting under the influence of changing ocean conditions is suspected as an additional key process, thus intensive research is underway in fjords near the front of calving glaciers (e.g. Rignot et al., 2010; Straneo et al., 2010; Straneo and Heimbach, 2013).

Detailed studies have revealed that ice mass change in Greenland is temporally and spatially heterogeneous

(e.g. Schrama and Wouters, 2011; Sasgen et al., 2012; Enderlin et al., 2014). Rapid loss was first reported in the southeastern area, and then spread to other regions along the coast. Mass loss has increased particularly in northwestern Greenland since 2005 (Khan et al., 2010; Kjær et al., 2012), but available data for the northern regions are generally sparse. Therefore, there is an urgent need to increase the reliable data for northwestern Greenland to quantify the mass loss and better understand the mechanisms driving recent changes in the region.

From 2011 to 2016, Arctic researchers in Japan collaborated under the integrated, multidisciplinary Green Network of Excellence (GRENE) Arctic Climate Change Research Project funded by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). As part of the GRENE research project “The role of Arctic cryosphere in global change”, we initiated a glaciological study in the region near Qaanaaq, a village in northwestern Greenland. The aim of the study was to quantify the ice mass loss in the region and understand its driving mechanisms. Here, we provide an overview of the GRENE Greenland project by summarizing the key findings of the study. We also provide an outline of our new project “Interaction of glacier/ice sheet and the ocean in northwestern Greenland”, which was launched in 2015 under the framework of the next Japanese national Arctic project “Arctic Challenge for Sustainability” (ArCS).

## 2. Study site

Qaanaaq is a village populated by  $\sim 600$  people, located in northwestern Greenland at  $77^{\circ}28'N$ ,  $69^{\circ}14'W$  (Fig.1). We selected this region as our study site because of the following factors: i) ice mass loss is increasing in northwestern Greenland; ii) only a few glaciological studies have been conducted in the region in the past; iii) Qaanaaq Airport is accessible by regular flights, and iv) Japanese researchers and explorers have been active in this region. Japanese activities in northwestern Greenland included a glaciological research at Site 2 by Ukichiro Nakaya from 1957 to 1960 (Nakaya, 1959) and pioneering dogsled expeditions by

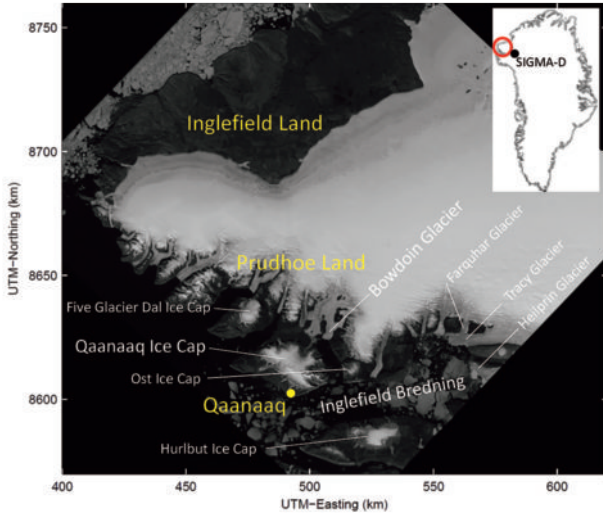


Figure 1 : Satellite image (Landsat 7 on 24 July 1999) of the Qaanaaq region in northwestern Greenland. The inset shows the locations of the study site in Greenland (circle) and the SIGMA-D ice core drilling site (dot).

Naomi Uemura in the 1970s (Uemura, 1974). More recently, a JSPS-funded research project on “Snow impurity and glacial microbe effects on abrupt warming in the Arctic” (SIGMA) has been carried out since 2011 (Aoki et al., 2014). The GRENE and SIGMA projects have closely collaborated over the 5-year period.

Qaanaaq is situated on the southern coast of a peninsula, facing the  $\sim 100$  km long and  $\sim 20$  km wide Ingfield Bredning fjord (Fig. 1). The northern bank of the fjord is named Prudhoe Land, where 19 calving glaciers flow into the ocean. Largest among those are Heilprin and Tracy Glaciers, which discharge icebergs into the eastern end of Ingfield Bredning at a rate greater than  $1 \text{ km a}^{-1}$ . Qaanaaq Ice Cap is located to the north of the village, covers an area of  $260 \text{ km}^2$ , and feeds numerous land-terminating outlet glaciers. Several other ice caps are situated in the region, including Hurlbut Ice Cap on an island to the southeast of Qaanaaq, and Ost and Five Glacier Dal Ice Caps on the main land adjacent to the ice sheet (Fig. 1).

Only a few scientific research activities have reported on the Qaanaaq region, particularly on its ice sheet and glaciers. Recently, satellite remote sensing on calving glaciers (Porter et al., 2014), airborne ice radar survey over the ice sheet (Palmer et al., 2013) and ocean measurements in Ingfield Bredning (Dybkaer et al., 2011) have been reported. Climatic data are available from the weather station at Qaanaaq Airport, which has

been in operation since 1996.

### 3. Ice caps

#### 3.1 Ice cap thinning in the Qaanaaq region

The ice caps in the Qaanaaq region are situated at an elevation range of  $0\text{--}1200 \text{ m a.s.l.}$ , where snow and ice melt is greatly influenced by recent warming. The rate of ice cap mass loss in northwestern Greenland is reported as  $0.6 \pm 0.1 \text{ m a}^{-1}$  for the period 2003–2008 (Bolch et al., 2013). We utilized a satellite image photogrammetry technique to investigate the mass change during a more recent period, and analyzed its spatial distribution, which was not resolved in the previous study. The focus of our study was six ice caps near Qaanaaq, i.e., Qaanaaq, Hurlbut, Ost, Five Glacier Dal, Kiatak and Steensby Land Ice Caps (Saito, 2015; Saito et al., 2016). We used stereo pair images from the Advanced Land Observing Satellite, Panchromatic Remote-sensing Instrument for Stereo Mapping (ALOS PRISM) to generate digital elevation models (DEMs) of the region for 2006, 2007, 2009 and 2010. Digital photogrammetry software (Leica LPS) and digital map plotting instruments (Planar SD2020 monitor and 3D Topo Mouse) were employed for this purpose. Surface elevation change over the ice caps was computed using the differences in the DEMs over time. DEMs generated by this method have an error of several meters in the vertical direction, but uncertainty in the elevation change decreases when they are averaged over the ice caps.

The result of the analysis revealed pervasive thinning of the ice caps in the Qaanaaq region (Fig. 2) (Saito et al., 2016). Mean elevation change over the six ice caps was  $-1.1 \pm 0.1 \text{ m a}^{-1}$  for the period between 2006 and 2010. This thinning rate is approximately twice that reported for 2003–2008 (Bolch et al., 2013), which confirms recent acceleration of the ice cap mass loss in the study area. Thinning is pronounced in the ablation areas, suggesting melt increase as a primary driver of the mass loss. Air temperature record at Qaanaaq Airport indicates an increase in summer temperature at a rate of  $0.12 \text{ }^{\circ}\text{C a}^{-1}$  over the 1997–2013 period. In addition to the atmospheric warming, albedo reduction also plays a role in the increasing melt rates. Bare ice is

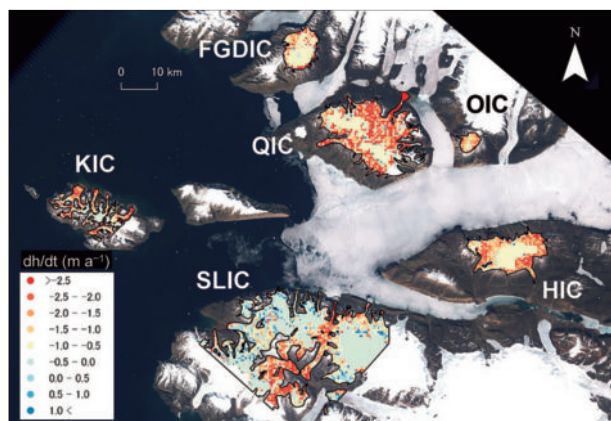


Figure 2: Rate of surface elevation change for the ice caps (IC) Hurlbut (HIC), Ost (OIC), Kiatak (KIC) (in 2007–2010), Qaanaaq (QIC), Steensby Land (SLIC) (2007–2009) and Five Glacier Dal (FGDIC) (2006–2010). Modified from Saito et al. (2016).

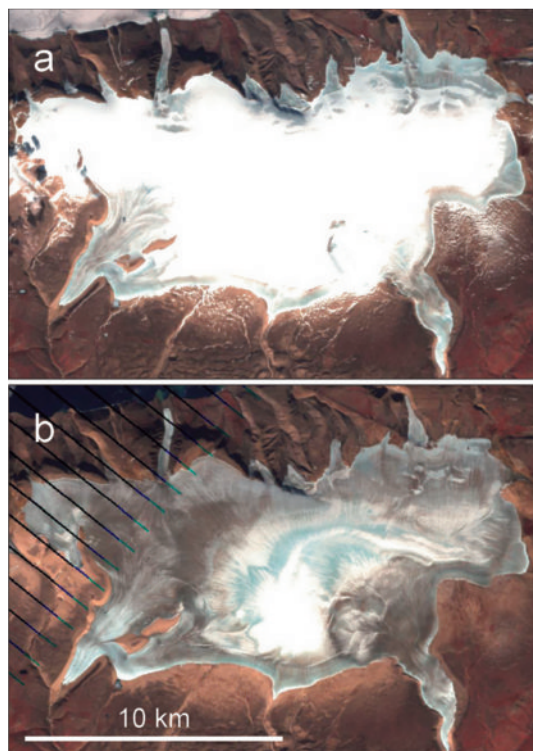


Figure 3: Satellite images (Landsat 7) of Hurlbut Ice Cap acquired on (a) 2 July 2002 and (b) 6 July 2012.

more exposed as the altitude of the equilibrium line increases, and the spatial coverage of glacial microbes on the ice surface increases (Takeuchi et al., 2014). These changes effectively reduce the surface albedo of the ice caps as represented by satellite images of Hurlbut Ice Cap taken in 2002 and 2012 (Fig. 3). The magnitude of the thinning was substantially different on each ice cap. For example, Qaanaaq Ice Cap thinned at a rate of  $1.8 \pm 0.1 \text{ m a}^{-1}$  from 2007 to 2010, whereas Steensby Land Ice

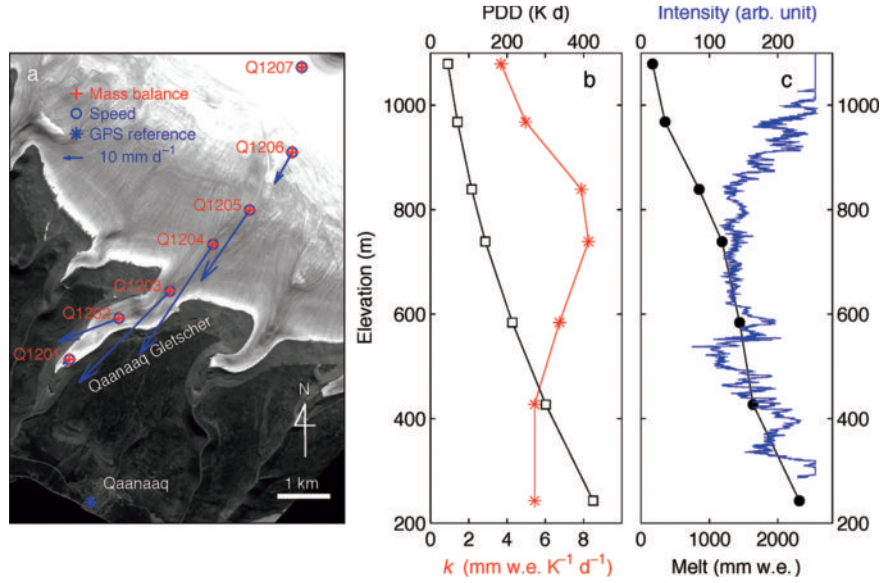
Cap showed a thinning rate of  $0.8 \pm 0.1 \text{ m a}^{-1}$  for the same period. Based on further satellite image analyses, we suggest relatively high albedo as a possible reason for the lower thinning rate observed on Steensby Land Ice Cap. In addition to albedo, regional variations in snow accumulation and glacier dynamics are other possible controls on the surface elevation change.

### 3.2 Qaanaaq Ice Cap

To monitor long-term variations in the surface mass balance and ice dynamics of Qaanaaq Ice Cap, we installed survey stakes on the ice cap and resurveyed the stakes every summer since 2012 (Maruyama, 2015; Matsuno, 2016). The stakes are located at elevations from 243 to 968 m a.s.l., spanning an area from the terminus of an outlet glacier (Qaanaaq Glacier) to a point inland, slightly higher than the equilibrium line altitude (Fig. 4a). Annual mass balance from 2012 to 2016 showed a large year-to-year fluctuation. During the study period, mass balance was most negative in the 2014/2015 season and most positive in 2012/2013. Specific mass balance at the lower most (243 m a.s.l.) stake was  $-2.10$  and  $-1.19 \text{ m water equivalent (w.e.) a}^{-1}$  in these 2 years, respectively. This result indicates the importance of long-term observations to capturing general trends of climatic and glacier changes. Our data from Qaanaaq Ice Cap form a part of only a few mass balance observations currently operated at marginal parts of Greenland (Machguth et al., 2016). We continue these measurements to help improve the accuracy of our understanding of the impact of changing climate on peripheral glaciers and ice caps in Greenland.

Field observations on Qaanaaq Ice Cap provided valuable information for understanding the processes controlling ice mass loss (Sugiyama et al., 2014). Summer melt rates at the survey stakes showed relatively high melt rates (i.e. large degree-day factors) at 500–900 m a.s.l. (Figs. 4b and c). Brightness intensity of a satellite image showed that ice in this elevation range was darker than in the other regions (Fig. 4c). This observation demonstrated a clear influence of surface albedo on the mass balance of the ice cap. We also determined summer (July) and annual ice motion by surveying the stakes using the global positioning system (GPS) to investigate a possible impact of surface





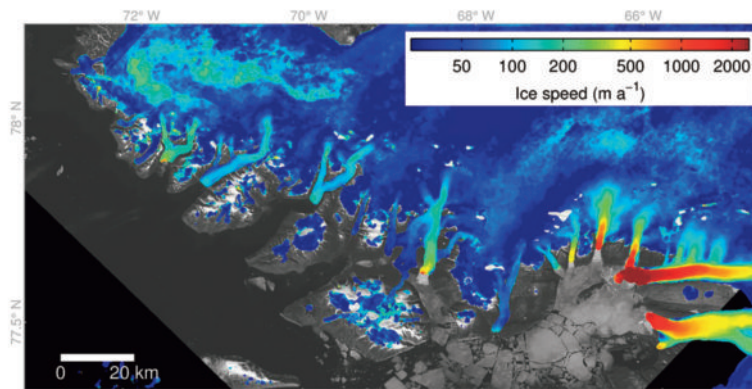
**Figure 4 :** (a) Satellite image (ALOS PRISM, 25 August 2009) showing the study area of Qaanaaq Ice Cap. Locations of the measurement sites for mass balance (+), ice velocity (O) and the GPS reference station (\*) are indicated. The arrows are horizontal surface flow vectors from 18–29 July 2012. (b) The positive degree-day sum (PDD) (box), degree-day factors (\*) and (c) total melt amount at Q1201–Q1207 computed for the entire summer melt season in 2012 (●). Blue line in (c) is the brightness intensity of the ALOS PRISM image shown in (a) along the survey route. Figures are modified from Sugiyama et al. (2014).

meltwater on basal sliding. Over the 4-year measurement period, ice motion accelerated only in July 2012 when Greenland was hit by an extreme melt event across nearly the entire ice sheet (Nghiem et al., 2012). The lack of summer acceleration in the subsequent years indicates the uniqueness of the meteorological conditions in the summer 2012, and it also suggests that the impact on the ice dynamics would be substantial if similar melt events will occur more frequently in the future.

## 4. Calving glaciers

### 4.1 Retreat, thinning and acceleration of calving glaciers

Another focus of our study was calving glaciers (Fig. 5). Most of the outlet glaciers in this region terminate in fjords, forming 0.6–5.0-km wide tidewater calving glaciers. According to our analysis using Landsat satellite images from 1987 to 2014, all of the 19 glaciers in the Qaanaaq region showed retreating trends after 2000 (Sakakibara, 2016). Some of the glaciers retreated more rapidly than the others, as represented



**Figure 5 :** Ice speed distribution over Prudhoe Land in 1987–2014 (Sakakibara, 2016). The speed was obtained by the feature tracking method applied on Landsat satellite images. Background is a Landsat 8 OLI image acquired on 9 July 2014.

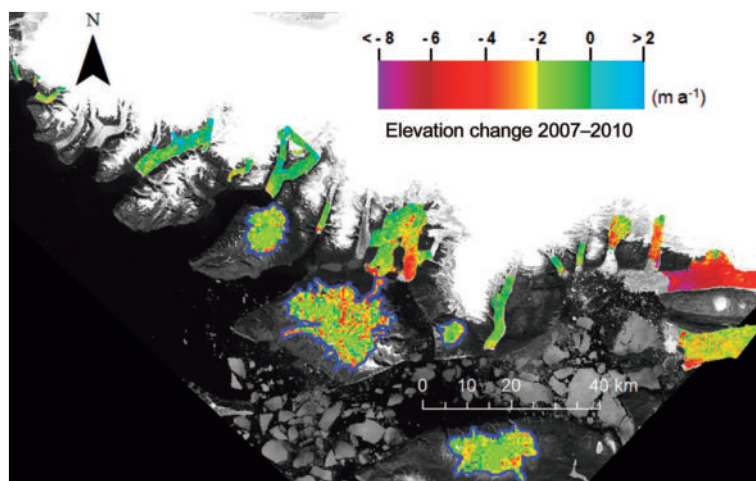


Figure 6 : Surface elevation change of calving glaciers and ice caps in the Qaanaaq region between 2007 and 2010.

by the more than 5-km retreat of Tracy Glacier during the study period. In general, glaciers terminating at the Inglefield Bredning fjord are retreating more quickly than those flowing into smaller fjords directly facing Baffin Bay.

The glacier retreat after 2000 accompanied ice thinning near the calving front. We employed the same DEM generation technique as for the ice caps to measure the surface elevation change of 14 glaciers over the period 2007–2010 (Katayama, 2016). Thinning rates are highly variable on each glacier, and higher thinning rates were observed at more rapidly retreating glaciers (Fig. 6). For example, Tracy and Farquhar Glaciers thinned at a rate of  $\sim 8 \text{ m a}^{-1}$  from 2007 to 2010, while they retreated by more than  $100 \text{ m a}^{-1}$  from 2000 to 2014. Several other glaciers were thinning at rates greater than  $5 \text{ m a}^{-1}$ . These rates are substantially greater than the surface mass balance at the elevation of the glacier termini, which is typically  $-2 \text{ m w.e. a}^{-1}$  in this region (Maruyama, 2015; Tsutaki et al., 2016). The magnitude of the thinning was greater near the glacier fronts. These results imply that the rapid thinning was primarily due to the increase in compressive vertical straining as a result of enhanced extending flow regime, so-called dynamic thinning.

Rapidly retreating and thinning glaciers are accelerating as well. Tracy, Heilprin, and Bowdoin Glaciers accelerated by  $> 10 \text{ m a}^{-2}$  from 2000 to 2014, and these glaciers retreated rapidly ( $80\text{--}340 \text{ m a}^{-1}$ ) over the same period (Sakakibara, 2016). The acceleration extended to

the region  $> 10 \text{ km}$  from the calving front, resulting in a large impact on the ice discharge and dynamic thinning. As it has been observed in other regions in Greenland, glacier retreat, thinning and acceleration are occurring concurrently in our study area. To understand the mechanism driving these changes, we performed intensive studies on Bowdoin Glacier.

## 4.2 Bowdoin Glacier

Bowdoin Glacier is one of the tidewater glaciers in the study area, located  $\sim 30 \text{ km}$  to the north of Qaanaaq. According to the comparison of an aerial photograph in 1949 and recent satellite images, the glacier front position experienced no significant changes for more than 50 years until it showed a  $\sim 200 \text{ m}$  retreat in 2000 (Sugiyama et al., 2015). The ice front remained at the same position until 2008, and then it retreated more than  $1 \text{ km}$  from 2008 to 2013 (Fig. 7). Ice speed showed a twofold increase from 1999 to 2002, and it maintained a fast flowing condition during the following period (Fig. 7b). Meanwhile, the glacier has been thinning at a rate ( $-4.1 \text{ m a}^{-1}$  from 2007 to 2010) substantially greater than that of the nearby land-terminating Tugto Glacier (Tsutaki et al., 2016). Surface ablation in the same region of Bowdoin Glacier was  $1.8\text{--}2.0 \text{ m a}^{-1}$  from 2014 to 2015, which accounts for only  $\sim 50\%$  of the observed thinning rate. According to the analysis of the ice flow regime, a large portion of the thinning was due to the dynamic thinning caused by the acceleration after 2000 (Tsutaki et al., 2016).

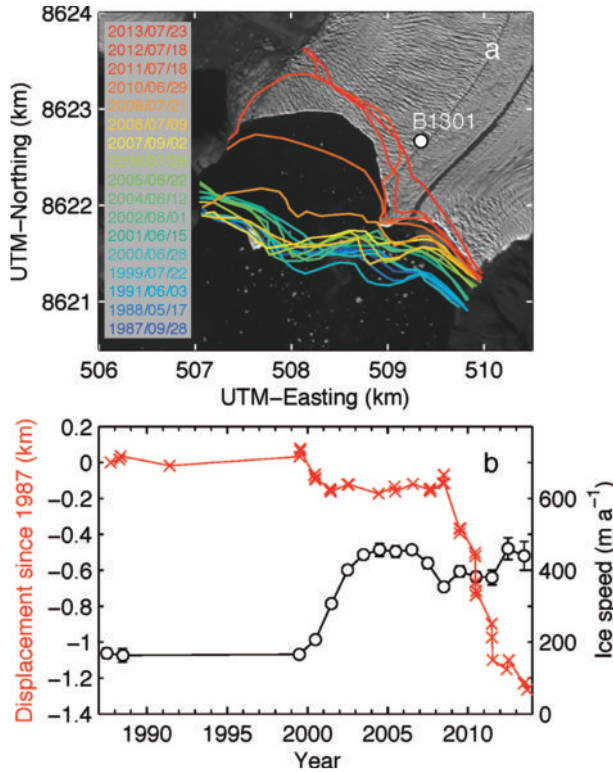


Figure 7 : (a) Frontal margins of Bowdoin Glacier observed from 28 September 1987 to 23 July 2013. Background is an ALOS PRISM image acquired on 25 July 2010. (b) The crosses are mean displacement of the glacier front since 28 September 1987. Negative change in the ordinate represents glacier retreat. The open circles are satellite-derived annual mean ice speed at site B1301 as indicated by the filled circle in (a). Reproduced from Sugiyama et al. (2015).

To obtain detailed information on glacier change, we performed field campaigns on Bowdoin Glacier in the summers 2013–2016. Ice thickness and fjord depth were measured near the glacier front, using a ground-based ice radar system and a sonar mounted on a small boat. The results revealed that the glacier front was very close to flotation ( $\sim 90\%$  of ice thickness was below sea level) and a  $\sim 50$  m high ocean bed bump was situated at  $\sim 1$  km from the ice front (Fig. 8). Ice speed was modulated by tides, surface melt and rain, implying that the force balance was susceptible to small perturbations (Sugiyama et al., 2015). Seismic measurements near the calving front showed that tidally modulated ice flow variation controls the frequency of ice fracture near the surface, which may have important implications for calving (Podolskiy et al., 2016). Infrasonic measurements were also performed to study the timing and locations of calving events (Podolskiy et al., this volume). In 2014, we drilled holes to the glacier bed with a hot-

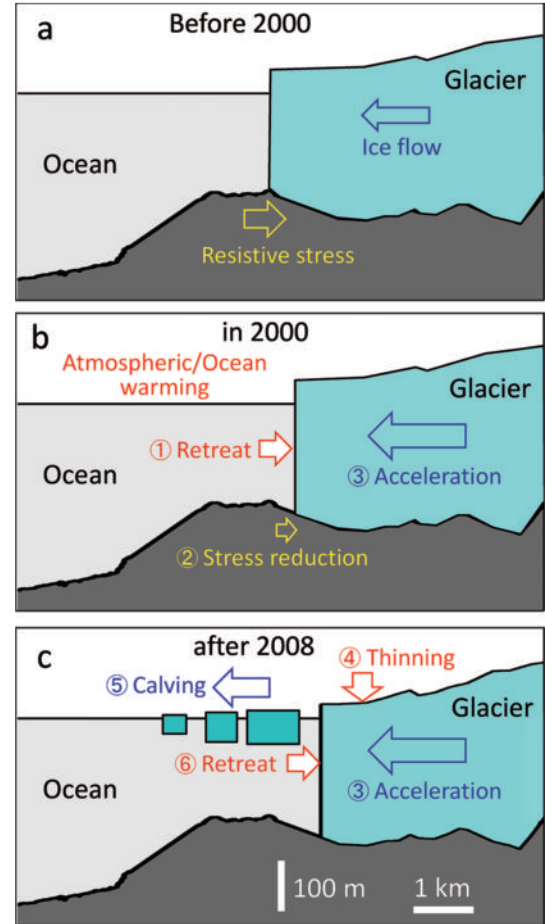


Figure 8 : Schematic diagrams showing the mechanism of the rapid retreat of Bowdoin Glacier since 2008. The diagrams show conditions (a) when the glacier was stable before 2000, (b) when the glacier retreated slightly in 2000 and (c) after the glacier began rapid retreat in 2008. The glacier and fjord geometry in (c) is based on field data.

water drilling equipment to explore subglacial and englacial environments. Borehole measurements confirmed that ice is temperate at the bed and that a subglacial hydrological system exists.

Based on the results of the field and satellite observations, we interpret the rapid retreat of Bowdoin Glacier since 2008 as illustrated in Figure 8. Before 2000, the glacier front was situated on the ocean bed bump, which stabilized the glacier front position for more than 50 years (Fig. 8a). Under the influence of atmospheric and ocean warming, the glacier front retreated slightly from the bump in 2000. The retreat distance was small, but the glacier force balance was strongly affected by the retreat of the ice front from the bump towards deeper water in upstream direction, resulting in rapid acceleration observed at the same time (Fig. 8b). After the acceleration, ice discharge increased and the



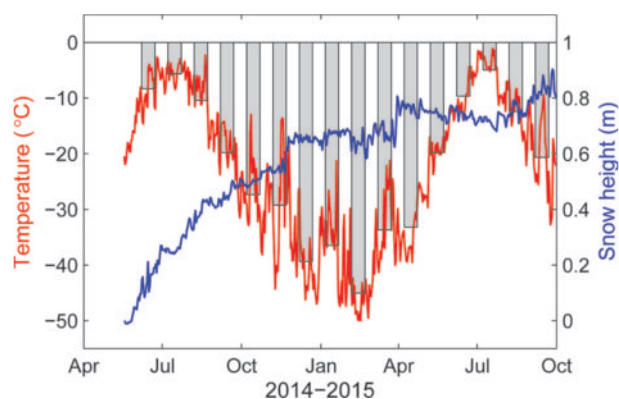
glacier progressively thinned until it reached the threshold of flotation. The rapid retreat initiated in 2008 when the glacier terminus began to float and then collapsed into the ocean (Fig. 8c). The detailed field and satellite data enabled us to propose this interpretation on Bowdoin Glacier. Similar observations on other calving glaciers will provide clues to predict the future evolution of calving glaciers in Greenland.

## 5. Atmospheric and ocean environments

### 5.1 Ice core and weather station

Compared with the melt increase clearly observed in lower-elevation areas, the changes in inland snow accumulation are less understood in Greenland. Because of the relatively complex coastal landscape in the Qaanaaq region, precipitation is spatially highly variable, and its temporal variations are not well known. To study snow precipitation and atmospheric conditions in the accumulation area, a 225-m-long ice core was drilled at 2100 m a.s.l. approximately 250 km east of Qaanaaq (Fig. 1 inset) (Matoba et al., 2015; Kadota, 2016). Drilling and other field activities were carried out from 5 to 26 May 2014. In addition to the drilling activities, GPS surveys were performed for surface elevation and ice flow in the region, and an automatic weather station was installed at the drilling site and operated until October 2015.

Figure 9 shows 2-m-height air temperature and snow surface elevation recorded by an ultrasonic ranger at the weather station from May 2014 to October 2015. Annual mean air temperature for the hydrological year



**Figure 9** : Daily (red) and monthly (gray bars) mean air temperature, and snow surface height relative to the surface on 18 May 2014 (blue) measured at the SIGMA-D site.

2014/2015 (from 1 October 2014 to 31 September 2015) was  $-25.9^{\circ}\text{C}$ , and summer mean temperatures (June–August) in 2014 and 2015 were  $-8.1$  and  $-9.0^{\circ}\text{C}$ , respectively. Daily mean temperature was below zero throughout the year, suggesting little influence of melt on the ice core. The snow surface rose by 0.8 m over the  $\sim 16$ -month measurement period, showing a highly variable snow deposition rate. For example, summer snow deposition (June–August) in 2014 was 0.36 m, whereas that in 2015 was less than several centimeters during the same period. These weather station data are crucial to analyzing the ice core, as well as to investigating climatological and snow deposition conditions in the accumulation area.

### 5.2 Ocean measurements

Calving glaciers are affected by ice front melting in the ocean, and in turn glaciers impact the ocean by discharging icebergs, meltwater and sediments. Therefore, it is crucial to investigate glacier-ocean interactions to predict the future of glaciers as well as the coastal environment in Greenland. Increasing numbers of fjord measurements are carried out in other regions of Greenland (e.g. Straneo et al., 2010), but such research is scant in northwestern Greenland. To study water properties in a glacial fjord, we performed conductivity, temperature and depth profiler measurements in Bowdoin Fjord. Temperature and salinity showed typical stratifications for glacier-fed fjords. The deepest region of the fjord ( $>290$  m) was filled with relatively warm and salty water ( $\theta=1.16\pm0.03^{\circ}\text{C}$ ,  $S=34.24\pm0.10$  PSU (practical salinity unit)), indicating intrusion of Atlantic Water into the fjord (Figs 10a and b) (Ohashi, 2015). Temperature and salinity decrease moving upward between the depths of 140–290 m under the influence of freshwater supplied from subaqueous melting. The coldest water, found at a depth of 50–110 m, is attributed to Polar Water originating from the Arctic Ocean. Above the Polar Water layer, highly turbid and fresh water was observed at 20–50 m (Fig. 10c) which we attribute to subglacial meltwater discharge. The turbid water was covered by the warmest and even fresher surface water (0–20 m). These observations are consistent with previously reported structures of Greenlandic fjords in other

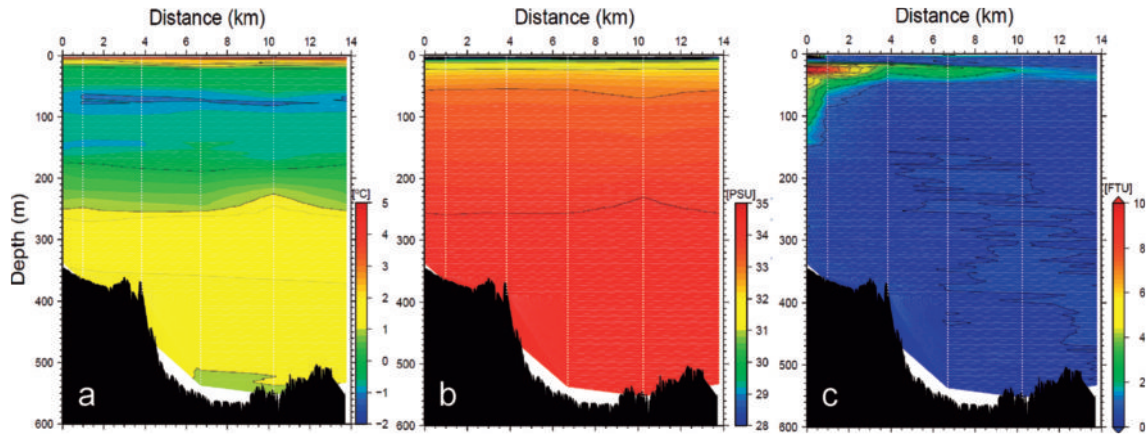


Figure 10 : (a) Potential temperature, (b) salinity in PSU (practical salinity unit) and (c) turbidity in FTU (formazin turbidity unit) measured in Bowdoin Fjord on 4 August 2014.

regions (e.g. Straneo et al., 2012; Chauché et al., 2014). Further measurements are needed in Bowdoin Fjord to understand the processes controlling subaqueous melting of the glacier and to monitor temporal changes in the water properties.

As a possible impact of glacier melt increase on the ocean environment, we studied turbid water discharge from glaciers into the ocean by analyzing satellite data from Moderate Resolution Imaging Spectroradiometer (MODIS) (Ohashi et al., 2016). The remote-sensing reflectance at the wavelength of 555 nm is commonly used to detect turbid water distribution, which we applied to the ocean surface in northwestern Greenland (76–78°N, 65–75°W). Highly turbid water was observed, particularly near the fronts of calving glaciers and the mouths of proglacial streams, indicating that the turbid water originated from sediment-laden glacier meltwater (Fig. 11). The turbid water spreads off the coast during the summer melt season and reaches its maximum extent in mid-July. The area covered by the turbid water showed large annual variations, and the summer maximum extent from 2002 to 2014 is positively correlated with summer mean temperature at Pituffik/Thule Air Base. This result implies that glacier melt controls the turbid water distributions, and sediment discharge into the ocean is likely to increase in the future as the climate continues to warm. We suspect that increasing sediment discharge has an impact on the coastal environment, which further affects the marine ecosystem in the region.

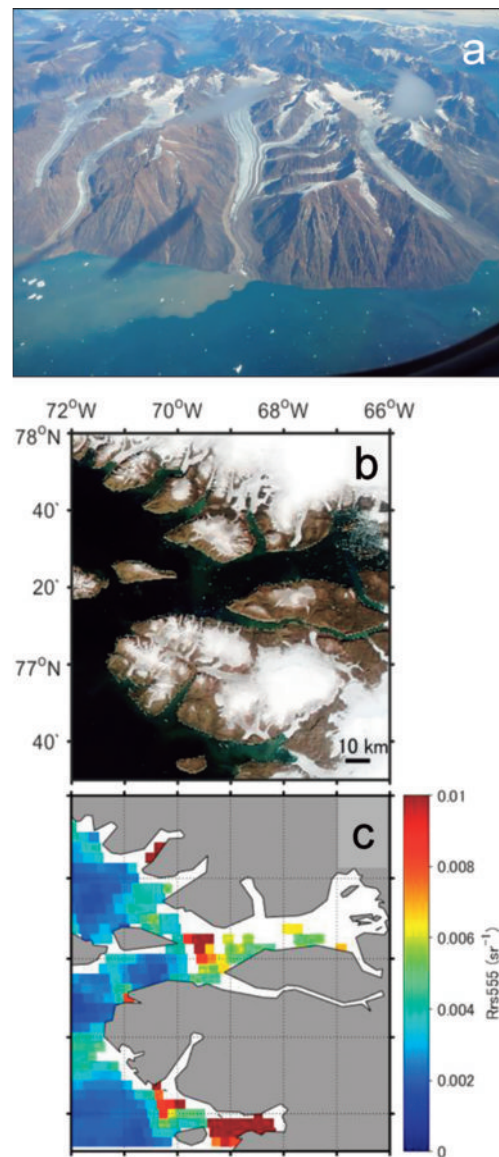


Figure 11 : (a) Turbid water discharge from a glacier in western Greenland (71.3°N, 53.0°W). The glacier length is about 10 km. (b) MODIS true color image of the study area and (c) Rrs 555 (remote sensing reflectance data at a wavelength of 555 nm). Land and ice sheet areas are indicated in gray. Modified from Ohashi et al. (2016).

## 6. Outlook of the ArCS project

The GRENE Greenland project focused on the changes in the ice sheet, glaciers and ice caps. Over the course of the study in the Qaanaaq region, we realized the importance of the interaction between the ice sheet/glaciers and the ocean. As mentioned above, submarine melting is suspected as a trigger for the recent retreat of the calving glaciers. Recent studies have indicated that ocean heat is efficiently transported to glacier fronts by fjord circulation, and the circulation is driven by subglacial meltwater discharge (Motyka et al., 2003; 2013). Furthermore, subglacial discharge upwells and forms a buoyant plume, which transports nutrient and plankton to the ocean surface, resulting in a unique marine ecosystem in front of calving glaciers (Lydersen et al., 2014). In fact, we observed abundant seabirds near the calving front of Bowdoin Glacier, suggesting that abundant fish and plankton are available in that region. Glacier fronts are also recognized by indigenous people as a good place to hunt sea mammals. Therefore, glacier changes have the potential to produce impacts not only on physical and chemical ocean conditions, but also on the unique fjord ecosystem. Our satellite analysis predicts an increase in sediment discharge into the ocean under warming climate. Such a change would affect the living environment of benthic fish in the fjords such as halibut, which is an important catch for fishermen in Qaanaaq.

After the GRENE project was completed, the Japanese integrated Arctic research was taken over by ArCS, a national project led by National Institute of Polar Research, Japan Agency for Marine-Earth Science and Technology, and Hokkaido University. In this new project, researchers' input is requested to aid stakeholders' and policymakers' decisions on sustainable development in the Arctic region. To achieve this goal, we continue our research in northwestern Greenland with a special emphasis on the ice sheet/glacier-ocean interaction. Furthermore, we investigate ocean environments and marine ecosystems, and the consequences of changes in these environments for the lives of people in Qaanaaq. In July 2016, we organized a workshop in Qaanaaq to present our scientific activities to the local citizens, and to exchange ideas and experiences about



**Figure 12 :** Workshop held in Qaanaaq on 25 July 2016. (a) Introduction of the research project and (b) comment from a local citizen. Photographs taken by Izumi Asaji and Bungo Nishizawa.

coastal environmental changes (Fig.12). Participants showed great interest in our study and described the impact of the rapidly-changing local environment on their traditional way of life. With a closer collaboration with social scientists, our next project aims to provide clues to help ensure a sustainable future for human activity in Greenland.

## 7. Conclusion

To quantify recent ice mass loss in northwestern Greenland, research was carried out in 2011–2016 in the Qaanaaq region under the framework of the GRENE project. Satellite image photogrammetry revealed thinning of ice caps in the region at a rate of  $-1.1 \pm 0.1$  m a<sup>-1</sup> from 2006 to 2010, which is nearly twice the rate reported for 2003–2008. Atmospheric warming is the primary driver of the acceleration of mass loss, but other processes including albedo reduction also play roles. Mass balance and ice speed measured on Qaanaaq Ice Cap have added to our understanding of the physical processes causing ice cap mass loss, and measurements



will continue to monitor these ongoing changes into the future.

Calving glaciers are retreating, thinning and accelerating. Some glaciers show rapid mass loss near the ice front, which indicates the importance of ice-ocean interaction for the glacier recession. Field campaigns and satellite data analyses on Bowdoin Glacier provided a comprehensive data set, which contributes to a better understanding of the mechanisms involved in the dynamics of calving glaciers in Greenland. Based on the observational data, we proposed a mechanism of the rapid retreat of Bowdoin Glacier that began in 2008. We also performed ocean measurements in Bowdoin Fjord and satellite analysis on turbid glacial meltwater discharge into the ocean. Our results demonstrated impacts of glacier discharge on the ocean environment. Further investigation is necessary on the interaction between ice sheet/glaciers and the ocean to understand ongoing changes in the coastal environment.

To investigate the ice sheet/glacier-ocean interaction and its consequences to the ocean environment and marine ecosystems, we initiated our next project under the framework of ArCS. In this project, we continue our research on the ice sheet and glaciers, and expand it further to the field of physical/chemical oceanography and marine biology. We collaborate with social scientists to determine the influence of environmental changes on human activities in Qaanaaq. Our project aims to acquire accurate data and improve understanding of ongoing change in the coastal environment, which should contribute to a sustainable future of the region.

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