An ice core on Müller Ice Cap

This project is a central component of Dr. Dorthe Dahl-Jensen's Canada Excellence Research Chair in freshwater-marine coupling. This 7-year program seeks to understand interactions between sea ice and glaciers in the Canadian Arctic and around Baffin Bay. The overall program focuses on how the high arctic ice caps have evolved over the past 20,000 years, and how these changes relate to variations in ocean temperature and sea ice. In addition to better understanding how the ocean and climate affect these ice caps, the project will improve understanding of how freshwater runoff from the ice caps affects the ocean properties of the Canadian Arctic. We plan to drill an ice core on Müller Ice Cap, Axel Heiberg Island (Figure 1), to determine how both sea ice and glacial conditions have varied over the time that the ice cap has existed. By measuring the chemistry, isotopes, and layer thicknesses of the core, we can gain a relatively complete picture of climate variations around the Canadian Arctic. In the short term, this ice core will give us records of various climate parameters (e.g., oxygen isotopes/atmospheric temperature and carbon dioxide), provide a proxy of sea-ice conditions, and give information about the age of the ice. Combined with radar data, the core will let us evaluate the overall history of the Müller Ice Cap. After addressing this short-term goal of making measurements with radar and the ice core in order to quantify climatic variations in the area, we will transition to the long-term goal of synthesizing this information to gain an overall understanding of the relationship between land ice, sea ice, the ocean, and the atmosphere in the high arctic. Given the relatively short span of observations of these remote ice caps, the long-term record of the ice core will be a key piece of the overall puzzle of ice-ocean interactions in the area.

Rationale

This work is motivated by the dramatic changes that the Arctic Ocean is undergoing as sea ice thins and retreats further north throughout the year. This sea-ice retreat changes the climate of the land surrounding the Arctic Ocean. Ice caps on these islands are thus retreating as they are exposed to warmer conditions and more melt. By studying cores from these ice caps, it is possible to retrieve records of past arctic sea-ice and climate conditions as well as information about the age and past ice-flow dynamics of the small ice caps, thus indicating their response to climate change. The long-term record provided by an ice core will offer unique insight into the interplay between these climatic variables, elucidating their relationship in a way not possible with modern observations alone.

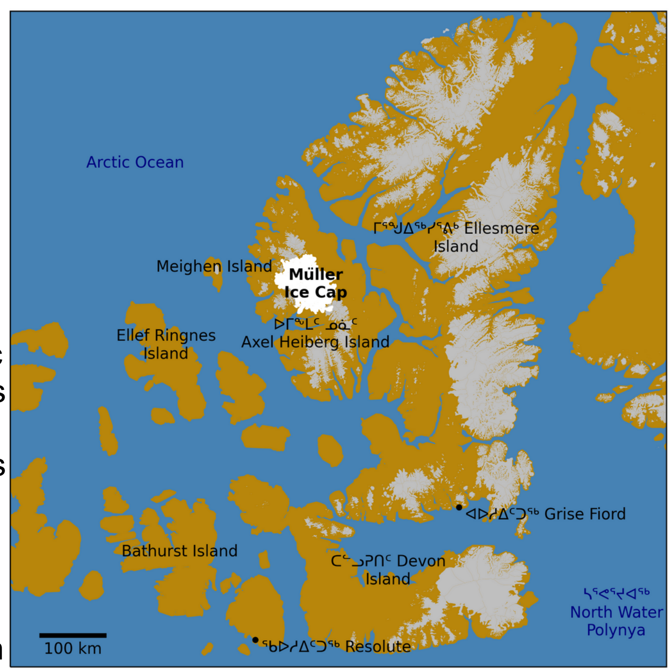

Figure 1: Location of Müller Ice Cap.

The Müller Ice Cap core will help answer:

- How did sea ice conditions change in the Arctic Ocean during the past 4,000-20,000 years, and what is the relationship between sea ice change and climate change?
- What climatic conditions did the arctic ice caps experience during that time?
- How sensitive are the arctic ice caps to changes in sea ice and climatic conditions?
- How old is Müller Ice Cap?

This project is motivated in part by the limited time remaining when such a record could likely be obtained. An ice core is only a useful climate record while the stratigraphy is still preserved, but melt resulting from the warming of the arctic would scramble the stratigraphy. Cores from other ice caps suffer from surface melt, which starts to refreeze deeper in the ice, thus mixing the annual layers. While its elevation and latitude mean that currently the top of Müller Ice Cap experiences only minor during mid-summer, we expect that it too will experience significant melt as the Arctic warms. Indeed, significant thinning of the ice cap's outlet glaciers is likely to propagate inland, causing changes to the centre of the ice cap over the coming decades. Moreover, our ability to measure proxies for sea-ice cover is relatively new (we plan to use techniques involving bromine (Vallelonga et al., 2021) and diatoms (Tetzner et al., 2022)), so the type of analysis that we plan, linking climate, ocean, sea ice, and land ice, has only recently become possible. We seek to take advantage of these overlapping windows, applying new techniques to understand the changing climate in the high arctic before that changing climate itself erases the evidence.

Methods

This project involves selecting a drill site, drilling the ice core, analyzing the ice we recover, and synthesizing those results to gain understanding of ice-ocean interactions.

During 2023, we plan to do the work needed to choose an optimal site for the ice core. Selecting the site for ice cores is an involved process that requires choosing a compromise between record length (in years) and resolution (how many years of climate record are contained in a meter of ice). For a given ice thickness, there is a tradeoff between resolution and length. For example, a place with high accumulation and a warm base may have a very short, high-resolution record, while a cold area with little accumulation will have a long, low-resolution record. We cannot measure the record length and resolution directly, but can use models to infer them based upon ice thickness, accumulation and melt (e.g., Lilien et al., 2021). To select the site for a core, it is usually necessary to go to the site to obtain detailed measurements of the ice thickness as well as the accumulation rate. Other parameters that are important for finding a good location, such as surface elevation, flow speed, and surface melt, can be measured from satellites; we have already done this remote-sensing work, as described below. The plan for 2023 involves both an aerial survey, to get the overall context, and a ground-based survey for the details.

The aerial survey will fly out of Resolute or Eureka in May 2023, never touching ground at our study site. The aircraft will fly at least 1200 ft above ground level, and will only operate instruments over the ice cap; total survey time is expected to be 6 hours. The survey will be flown by a Basler (Turbo DC3) from the Alfred Wegener Institute operating an ultra-wide band radar, a laser altimeter, cameras, a thermal infrared sensor, and basic meteorological instrumentation. The radar operates from 150 to 600 MHz with 4 kW peak transmit power; it is safe for humans and animals at any range. The laser altimeter is eye safe at distances over 351 ft; the flights will be high enough that the laser poses no risk to any people or animals on the ground, and moreover it will only be on over the ice cap. The camera, infrared sensor, and meteorological instruments are passive, and thus also have no impact on any people or animals who happen to be on the ice cap. The planned survey lines are shown in Figure 2.

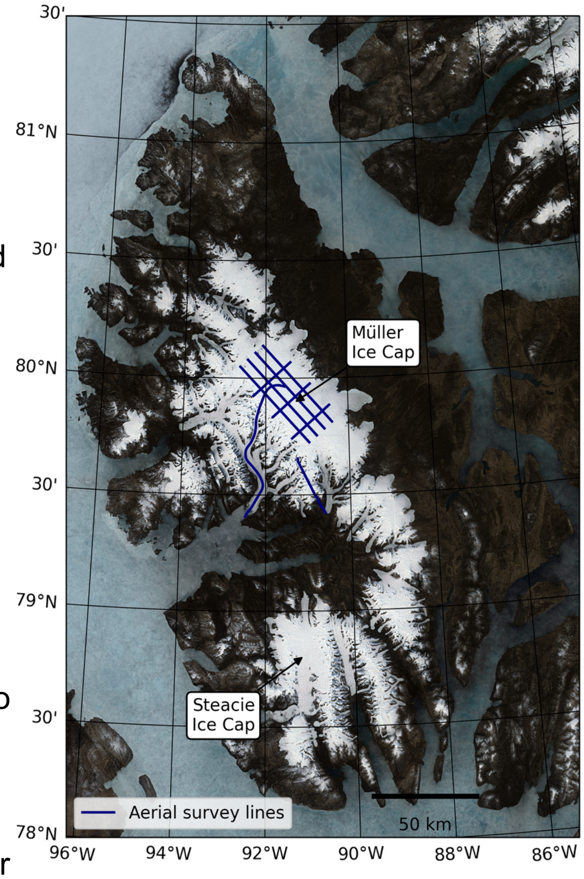

Figure 2: Planned survey flights for 2023, flying from Resolute or Eureka.

We plan to send a team of five people to Müller Ice Cap in 2023 to measure the parameters for ice-core site selection that can only be measured from the ground. This team will drive a radar survey using a powerful new high-resolution ice-penetrating radar operating from 180–480 MHz (Yan et al., 2020). This system will allow us to measure the ice thickness as well as stratigraphy in the ice, which will help in selecting a site with undisturbed layering. The team will drive about 250 line-km of radar (towing the radar behind a snowmobile); initially we plan to survey all the area above 1600 m (Figure 3a) using 2.5 km track spacing. After processing this data at our campsite, we will identify the most promising area for an ice core, and drive a fine, 500-m radar grid so that we can select an exact site for drilling. In addition to driving radar, the field team will make a number of surface measurements to aid in the site selection. Primary among these, they will hand-drill 2–5 10-m cores, on which we will measure density, dust, and conductivity; these cores will be measured in the field using a portable instrument (Kjær et al., 2021). The measurements of these cores will constrain the accumulation rate and how it varies spatially, and will identify where surface melting might affect core quality, helping us to pick an optimal drill site for the following year. We will complement these 10-m cores with snow pits and probing of the past summer's surface, allowing us to gain a relatively complete picture of recent variations in snowfall and melt. From this first trip to the ice cap, about 100 small (50 ml), melted samples will be taken back to the lab for further analysis of chemistry and continued development of proxy methods to determine sea-ice concentration. In total, we plan for 16 days camped on the ice cap with a team of 5.

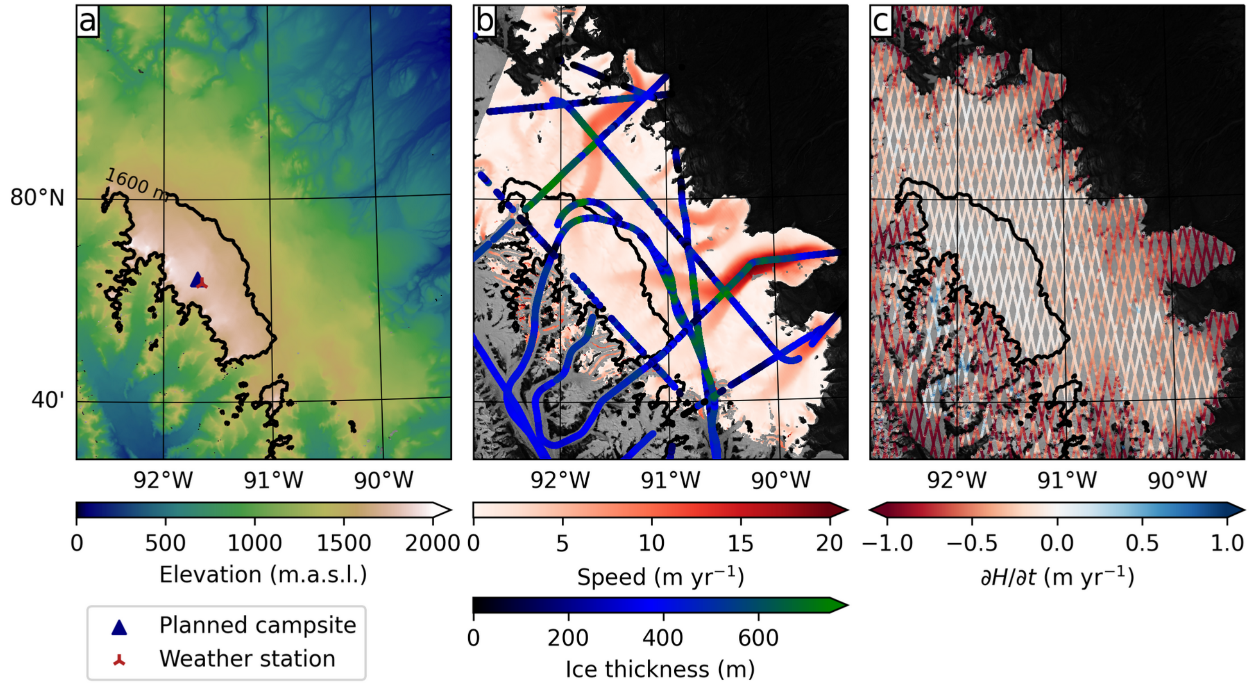

Figure 3: Remote-sensing observations of Müller Ice Cap. ***a*** *Surface elevation, with contour showing 1600 m (the minimum elevation expected to be suitable for drilling). Blue triangle and orange marker show our planned campsite and the Queen's University weather station, respectively.* ***b*** *Ice-flow speed derived from InSAR using Sentinel-1. Blues and greens plotted on top show ice-thickness measurements from NASA's Operation IceBridge and the British Antarctic Survey (Paden et al., 2018).* ***c*** *Annual change in ice thickness from 2018 to 2022 derived from NASA's ICESat-2 (Smith et al., 2022).*

In 2024, we plan to drill the ice core itself. Based on existing radar data, we expect to find a drill site with ice approximately 600 m thick (Figure 3b), this is very similar to Renland Ice Cap in Greenland, where a team from Dr. Dahl-Jensen's group in Copenhagen drilled the "ReCAP" ice core over the course of 2 months in 2015 (Vinther, 2016). We have based our logistical plans for Müller Ice Cap on that project. This work will follow established methods for deep drilling, using a drill designed and built by Dr. Dahl-Jensen's group in Copenhagen; this drill has been used successfully in Greenland and Antarctica, and is also the basis for designs now used by drilling groups in the USA, Japan, and Germany. The drill is suspended on a cable, and recovers a 10-cm-diameter core of ice in 1–3 m sections on each trip down the borehole (thus, a 600 m core is recovered by hundreds of short trips of the drill down the hole). To drill to these depths, it is necessary to use a drill fluid in the hole; this prevents the ice pressure from closing the hole. We plan to use Estasol-140, a drill fluid with a low freezing point and similar density to ice. Estasol is considered non-hazardous and biodegradable and has been used and left in the borehole in Greenland (including the protected Northeast Greenland National Park) and in Antarctica, and has become the international standard in ice-core drilling; we plan to leave the drill fluid here as well, both to allow future logging of the hole and because it is generally impractical to remove all of it. We expect to have a team of 12 on the ice for 2-3 months (depending on the actual ice thickness found) to drill the core. The ice core itself will be cut into short sections and to shipped back frozen to laboratories in Canada and Europe for analyses. The total volume of ice removed will be less than 10 cubic meters, and a full archive (covering all depths) will be preserved at the Canadian Ice Core Laboratory for future analyses.

In addition to the deep ice core, a shorter 100 m ice core will be drilled without the use of drill liquid. As the ice core is being drilled the greenhouse gas concentrations in the snow and ice will be measured to understand how the gas is trapped in air bubbles with depth. The ice core will also be cut in short sections and shipped back to provide more material for measurements in this top part of the ice cap representing the climate the last few hundred years. Analysis of the cores will include all the standard ice-core measurements, complemented with new methods used to understand past sea-ice conditions. The standard parameter suite we will measure includes physical properties, chemical and isotopic properties of the ice, and concentrations of greenhouse gassed of the air bubbles contained within the ice. We will follow similar protocols to other major ice-core efforts, where we first establish a detailed sampling plan for the core, allocating specific slices for each of these measurements and for archiving. Physical properties we will measure are: electrical conductivity measurements (ECM), dielectric properties (DEP), linescan (i.e. high resolution, backlit imagery along the whole core), and ice-crystal fabric (i.e. the orientation of the *c*-axes of the ice crystals). These four measurements all follow standard techniques but require specialized equipment; the needed instruments belong to University of Manitoba, University of Alberta and our international partners at the Alfred Wegener Institute in Germany and at the University of Copenhagen. We will measure major chemical species in the ice core (e. g. sulfur, calcium and chloride) as well as dust concentration using mass spectrometers and laser technics. We will measure deuterium and oxygen isotopes using cavity ringdown spectrometers; the relative abundance of deuterium (δd) and oxygen 18 ($\delta^{18}O$) will provide a proxy for past temperature. In addition we will measure mercury concentrations using an inductively coupled plasma mass spectrometer (ICP-MS). Measurements of these chemical and isotopic properties of the ice will be performed at the University of Manitoba and the University of Copenhagen. As the core is melted for measurements on the resulting water, the properties of the air contained in the bubbles will be measured as well. In this gas, we will measure concentrations and isotopes of greenhouse gasses like carbon dioxide, methane and N_2O. In addition to these now-standard measurements, we will gain unique insight into sea-ice history using two new proxies for sea-ice concentration. The first method involves measurements of bromine and iodine in the ice (Vallelonga et al., 2021); these halogens essentially show the proximity of open water to the ice-core site (since they originate from salts), and their concentration can be measured using an ICP-MS. In addition, collaborators at the University of Copenhagen are developing methods to determine sea-ice concentration from diatoms in the ice (diatoms are thought to be deposited by winds coming from open water (Tetzner et al., 2022) and thus can indicate sea-ice cover). We plan to use a scanning electron microscope (SEM) to measure diatoms in discrete, filtered samples of melted ice to provide a second record of sea-ice concentration.

As these results come in, we will begin to address the overall goals of the project, synthesizing the datasets to improve understanding of interactions between sea ice,

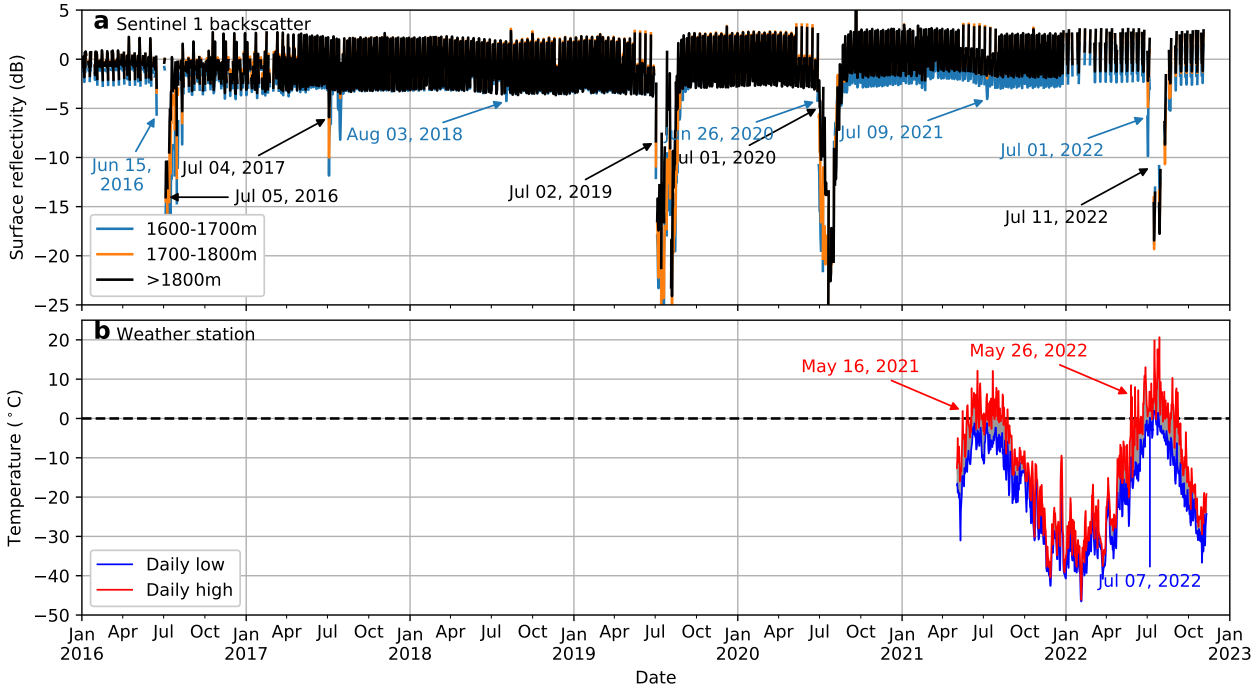

Figure 4: Melt at the top of the ice cap. ***a*** *Backscatter from Sentinel-1. Values below -5 indicate widespread melt. Different coloured lines indicate different elevation bands.* ***b*** *Temperature from Queen's University weather station (at 1850 m above sea level).*

climate, and land ice during the time period spanned by the ice core. A first step in this synthesis will be comparing the multiple proxies for sea ice, and making a robust determination of the trends and variability in Arctic sea ice cover over the time period spanned by the ice core. We will then examine correlations between sea ice and the climate proxies in the ice core (e.g. $\delta^{18}O$) to determine how these changes relate to climatic forcing. Additionally, the relationship between sea ice and land ice will be evaluated in order to determine whether the drivers of change are the same over the ocean and over land. In addition to this detailed comparison between the records recovered from the ice core, the long-term information will be contextualized using observations of present-day interactions between Müller Ice Cap and the ocean. This work, examining the modern-day relationship between the ice cap and ocean properties, has already begun, as described next.

Progress to date

To date, our work has focused on remote sensing observations of Müller Ice Cap for the ice core, direct examination of freshwater-marine interactions at the edge of the ice cap, and investigating the processes that drive the formation and release of bromine and other tracers from the marine environment and their subsequent transport to and deposition in glaciers. This past summer, a small field team went to Expedition Fjord to: collect physical ice and snow samples from various ice types and along a transect from the marine to glacial environment for biogeochemical analysis, specifically nutrients, bromine, and other freshwater tracers; characterize the spatial variability in sea-ice thickness and snow depth in the area. Initial results from this work show layers of Pacific and Atlantic water present in Expedition Fjord, with some freshening that may be due to glacial meltwater; we are continuing to investigate how the meltwater runoff from the ice cap affects ocean properties in the area.

Our work evaluating Müller Ice Cap for ice-core drilling has shown that the summit of the ice cap is generally free of melt, is moving less than 2 m/yr, and has pockets of ice at least 600 m thick, sufficient for a high-quality ice core record. In addition, we have evaluated ice-thickness changes over the last decade and found that the top of the ice cap (>1800 m) has very stable thickness while there is slight thinning of up to 10 cm/yr between 1600 and 1800 m; this corroborates the finding of little melt but suggests that melt may begin to affect the top of the ice cap in the coming decades. Collaborators at Queen’s University have been to the top of the ice cap and they found minimal evidence of melt in the snowpack (only some faceted crystals) during 2021, and they also installed a weather station on top of the ice cap. Data from the station show that daily highs rise above 0ºC frequently during the summer months, even at 1850 m. This relatively short time series was extended with radar remote sensing; surface reflectance generally drops in the presence of widespread melt, so melting can be detected with radar satellites such as Sentinel-1. Comparison of weather-station data and Sentinel-1 surface reflectance indicates that, in the one year with data available, a drop in surface reflectance corresponds with the night time low rising above 0ºC (Figure 4). The Sentinel-1 data indicate no widespread melt above 1800 m in 2021, consistent with the colder temperatures observed in that year compared to 2022. However, there was somewhat more substantial surface melt in five of the seven years with satellite observations. Taken together, these data indicate that the area currently has little enough melt to preserve a useful climate record, though that may already be changing rapidly, and relatively little warming may result in significant melt at the top of the icecap.

Data

We anticipate at least five main datasets from this project: 1. radar information about ice thickness from airborne and ground-based surveys 2. proxy sea-ice variability measurements 3. ice-core chemistry and isotopes 4. ice-core gas measurements, and 5. an archival portion of the core itself, spanning all depths. The first four will all be made publicly available on the Canadian Watershed Information Network (CanWIN). CanWIN is hosted by the University of Manitoba, and allows users to search for data geographically or by keyword. The archival portion of the core will be stored in the Canadian Ice Core Lab in Calgary, and will be available for future researchers to request access for analyses.

The modeled data produced from the use of the ice core datasets mentioned above will contain information on the past and present temperature, precipitation, pollution (e.g. mercury), greenhouse gas concentrations as well as the evolution of the ice cap.

The data will be presented to the communities through consultations. Together with past knowledge from the communities on changes of ice and temperature near Grise Fiord and Resolute future community-led research can be initiated. Particularly if our CFI Baffin Bay North proposal is successful (evaluation results expected June 2023), we will be able to build joint research programs involving the communities building upon the results from Müller Ice Cap.

Research outputs

Several student theses have been supported during the planning stages of this project, with many more planned as the project progresses. One masters student (Anne-Sofie Zinck) was supported in Copenhagen to look at the existing information about ice thickness in the area. A masters student (Christian Phillips) at the University of Manitoba did initial age modeling of the ice cap. One PhD student (Niels Nymand) will process and interpret the radar data from 2023 as one chapter of his dissertation. Another PhD student's dissertation will focus on developing the diatom-based proxy for sea ice. Additional Master and PhD students will will be involved in the analyses of the ice core records and the modelling. Involvement of youth from the communities in fieldwork and analysis of the data has high priority.

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