MONITORING GLACIAL ALGAE AND IMPURITIES ON THE GREENLAND ICE SHEET

Scientific Report from DCE – Danish Centre for Environment and Energy No. 489 2022

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Data sheet

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Abstract: This project initiated a pilot study for sampling biological growth, alongside the Programme for monitoring the Greenland ice sheet (PROMICE) to better understand the interplay between climatic factors and physical, chemical and biological processes that contribute to surface melting of the ice sheet. The results in the project show that direct sampling of ice surfaces during PROMICE missions provide important information to characterize the surface darkening where local weather data are available.

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Forord/Preface

This report documents initial investigations and recommendations for establishing a biological and related abiotic impurities monitoring programme on the Greenland ice sheet (PROMBIO). Its main purpose is to test a methodological procedure to sample ice surfaces in connection with the maintenance of the PROMICE and GC-Net automatic weather stations operated by GEUS.

This report is funded by a grant from the Klimastøtten til Arktis to Prof. Anesio for the project “PROMBIO – Programme for monitoring of biological and abiotic impurities on the Greenland ice sheet”. Fieldwork and travel associated with the test of methodologies and sampling were co-funded by the European Research Council (ERC) Synergy grant under the European Union's Horizon 2020 research and innovation programme under grant agreement No 856416 (Deep Purple - Darkening of the Greenland Ice Sheet) and PROMICE. Deep Purple puts together an international team of scientists to investigate the physical and microbial processes that darken the Greenland ice sheet that can accelerate sea level rise, while the main mission of PROMICE is to monitor and understand the Greenland ice sheet mass balance, as well as to support international projects and assessment reports enhancing Danish involvement in global decision-making.

Sammenfatning

Området med mørk is langs kanten af Grønlands indlandsis er steget over de seneste 20 år, hvilket har ledt til en stigning i afsmeltningen i sommermånederne. Det er nu velkendt, at væksten af kraftigt pigmenterede alger, sammen med en forlænget snefri varighed, er en afgørende faktor for mørkfarvningen af barisområdet. Dette projekt igangsatte et pilotstudie om prøvetagning af biologisk vækst sammen med indlandsisovervågningsprogrammet (PROMICE) for bedre at forstå samspillet mellem klimatiske faktorer og fysiske, kemiske og biologiske processer, der bidrager til issmeltning. Resultaterne af projektet viser, at direkte prøveudtagning af isoverflader i forbindelse med PROMICE-moniteringen giver vigtig information i forhold til at kunne karakterisere det område, hvor lokale vejrdata er tilgængelige. Rapporten indeholder også anbefalinger til overvågning af biologisk og abiotisk forurening på Grønlands indlandsis ved hjælp af yderligere måleinstrumenter på faste stationer, der bedre kan skelne biologiske og abiotiske signaturer.

Summary

The area of dark bare ice along the margins of the Greenland ice sheet has increased in the past 20 years, facilitating an increase in melting in the summer months. It is now well recognized that growth of strongly pigmented algae, along with an expanding snow-free duration, is a leading factor in the darkening of the bare ice area. This project initiated a pilot study for sampling biological growth, alongside the Programme for monitoring the Greenland ice sheet (PROMICE) to better understand the interplay between climatic factors and physical, chemical and biological processes that contribute to surface melting of the ice sheet. The results in the project show that direct sampling of ice surfaces during PROMICE missions provide important information to characterize the surface darkening where local weather data are available. In addition to the direct sampling approach, the report also considers recommendations necessary for monitoring biological and abiotic impurities on the Greenland ice through additional instrumentation at fixed stations that can better distinguish biological from abiotic signatures.

1 Introduction

In a recent scientific report from the Danish Center for Environment and Energy (DCE), Anesio and Cook, 2022 describe the importance of biological impurities on the melting of the Greenland ice sheet. The current literature information makes a compelling case that the presence of pigmented glacier ice algae on ice surfaces has a significant impact on the darkening of the ice and thus, its melt (Cook et al., 2020; Stibal et al., 2017; Williamson et al., 2020; Yallop et al., 2012). While an accurate method for remote sensing quantification of biological impurities on ice surface remains unavailable, we heavily rely on sampling of ice surfaces for quantification of glacier ice algae. However, direct sampling of ice surfaces is scarce and not systematically capturing seasonal, inter-annual or spatial variabilities. Furthermore, different studies performed by different research groups have very different ways of sampling the ice surface, which can then make comparisons difficult. The heterogeneous distribution of inorganic particles and biological impurities on ice and snow surfaces is a major challenge for establishing quantitative comparisons between different studies. Both the area and depth of the surface snow or ice sampled can influence algae cell counts per volume or area basis by orders of magnitude. For instance, abundance of glacier algae collected along the same region on the Greenland ice sheet varied between <100 to 8.5 x 10^7 cells L^{-1} of melted ice, but could reach up to 1.8 x 10^8 cells L^{-1} at sites that were visually darker in appearance (Stibal et al., 2017). Similarly, Williamson et al. (2018) reported variable cell abundances from the same location as in Stibal et al. (2017); between 0 and 1.6 x 10^7 cells L^{-1}. While seasonality and annual trends likely influence algal abundance and thus the biological albedo reduction (Tedstone et al., 2017), part of the documented variability in algal abundance is due to differences in sampling procedures. The lack of comparable data using different methods (e.g., direct sampling of the ice, remote sensing) limits large spatial and temporal scale comparisons between studies. This also applies for all other analyses of snow and ice habitats (e.g., nutrient contents and distributions, inorganic particle loads, black carbon, etc.) where sampling, sample handling, sample preservation and sample analyses procedures also vary, from team to team, from site to site, and from habitat to habitat. For example, it is easier to consistently sample the top 1-2 cm of a relatively flat snow surface than the 1-2 top cm of a relatively rough ice surface. Comparing any resulting physical, chemical, or biological data sets is also hindered at the later sample handling stage where for example, mode or material of filtration units or sample preservation vary.

Our ability to monitor algal counts on ice surface and infer the impact of climate warming on algal growth is constrained by the fact that there are no sustained monitoring programs associated with the collection of biological data on glaciers and ice sheets. Weather stations on the Greenland ice sheet e.g., the PROMICE program (promice.dk) already provide a long-term data set of local temperature and other weather-related data that, if associated with a robust sampling program for biology and other particulates, could fill the current data gaps preventing us from monitoring algal growth on the ice. Satellite imagery and advances in time-lapse photography could also bolster temporal and spatial records of potential biological darkening of the ice, but this needs validation with ground truth data. Considering that bare ice areas available for algal proliferation and the length of the active growth season are

set to expand in the future, the likely expansion of biological darkening cannot be ignored by predictive models.

In this study, we report the first steps of PROMBIO (Programme for Monitoring Biological Impurities on the Greenland ice sheet) that links biological monitoring with the PROMICE (Program for Monitoring of the Greenland Ice Sheet) stations, providing a link between weather and albedo data with algal numbers. This data would, in the long term, provide the necessary links of glacial algae presence with satellite imagery to allow whole-ice sheet spatial and temporal scale measurements and prediction to occur. However, in order to do so, it is necessary first to establish methodologies and procedures for data collection. This report documents the pilot-study work on the Greenland ice sheet that began to establish methodological procedures necessary for monitoring the abundance of biological and abiotic impurities on the Greenland ice sheet and provide recommendations on how to implement such a monitoring programme. Samples were collected for algal counts and other microscopic observations as these are the most important information for albedo determinations and also the most practical set of analyses that are possible within the remit of PROMICE. In the future, where possible, analyses of microbial diversity using next generation sequencing techniques, pigments and organic and inorganic chemical characterization of ice surfaces should also be considered.

2 Methods

2.1 Theoretical framework for selection of a direct sampling method of ice surface for microbial counts

A methodological procedure for monitoring glacier ice algae and abiotic impurities in the vicinity of the PROMICE and GC-Net stations (https://promice.org/weather-stations/) was the main goal of this project. The maintenance routine of the weather stations by the Geological Survey of Greenland and Denmark (GEUS) on the Greenland ice sheet were considered an excellent opportunity for the simultaneous collection of biological and abiotic impurity data of the ice surface. Direct sampling of the ice surface for quantification of algae needs to conform to the very limited ground time of maintenance visits (0.5 to 4 hours) and associated time and financial costs of adding a new task to the current routine maintenance, manpower available during the fieldwork, sample preservation, sample volume, level of information provided and simplicity. Constraint is recognized for returning from the field with ice samples. Keeping any samples cold during transport back to the laboratory for analyses in Denmark is a challenge. Mostly important, the sampling method needs to be straightforward and time-efficient.

After discussions with personnel from GEUS and in order to fit with the maintenance schedule of the weather stations, the method for sampling had the following basic requirements:

- **Duration of sampling effort**: under 10 minutes

- **Volume**: as little as possible, but not under 5 ml per sample (ice equivalent)

- **Reproducibility**: a specific area and depth of the ice should be consistently sampled with an acceptable accuracy.

- **Simplicity**: the procedure should be easy to communicate between different members of the team involved in the weather station maintenance.

- **Equipment size:** the size of the equipment should not add unreasonable extra payload to the helicopter.

In this project, three procedures for sampling collection were considered, of which two were discarded at the planning stage due to their significant deviation from the basic criteria. The three methods attempted were:

a) **Ice sampling device:** In collaboration with the Department of Engineering at Aarhus University, A prototype of sampling device was designed and tested. While it produced promising results in terms of reproducibility of specific area and depth of ice surface sampled, it failed in time spent, simplicity and size specifications. Therefore, this approach was disregarded.

b) **Ice Scraping:** This has been the most common procedure used in a range of studies for collection of biological and abiotic material from ice surfaces (e.g., Holland et al., 2019; Nicholes et al., 2019; Perini et al., 2019; Stibal et

al., 2017; Williamson et al., 2018). It consists of using an ice axe or chisel to gently scrape a specific area of the ice surface at the lowest depth of the ice as possible into a sterile bag (Figure 2.1). Despite its simplicity, the method fails in other basic parameters (i.e., time spend to collect sample, volume and reproducibility). Although the area of the ice scraped can easily be adjusted, it was difficult to balance precision and volume issues. On one hand, scraping of smaller surface areas, which contributes to smaller volume of samples, results often in poor reproducibility of the area sampled. On the other hand, scraping of large surface areas, although resulting in better precision of the area and depth of sampled ice surface, it also takes longer time and results in larger volumes of sample, increasing payload in the helicopter in the return trip.

Figure 2.1. Photo of ice scraping procedure using an ice axe. The sampling procedure is ideal for analyses that require large volume of samples, such as DNA, quantification of particulates, elemental analyses, metabolomes (e.g., Lutz et al., 2015, 2016).

c) **Ice screw:** This method was first used by Yallop et al. (2012), which is one of the first studies quantifying and demonstrating the importance of glacier ice algae on the darkening of ice surfaces on the Greenland ice sheet. This method consists of pushing an ice screw at the ice surface to remove ca 2 cm of the top surface and place into a sterile sampling tube (Figure 2.2). The ice screw method meets the speed, volume, and simplicity requirements and has an acceptable margin of error in terms of reproducibility.

Figure 2.2. Photo of the ice screw and sampling bag on the right (Photo: Alexandre Anesio) and of the ice screw procedure conducted by GEUS during the PROMICE weather station maintenance on the left (Photo: Jason Box). The sampling kit is easy to carry and procedure for sampling is fast and simple.

2.2 Fieldwork and sample collection

The final field study used the PROMICE weather station at the QAS-M area (61.0998 N, 46.8330 W, 630 m elevation) as a baseline to test the ice screw sampling for glacier algae counts (Figure 2.3). The ice camp established by the Deep Purple ERC-Synergy was used for collection of samples in the area to investigate the efficiency of the ice screw method in comparison to the ice scraping method, and to account for the heterogeneity and spatial distribution of glacier ice algae and other abiotic impurities. Preparation and tests were conducted between 20th and 30th of July, while sampling was conducted on the 31st of July 2021. Between 31st of August and 2nd of September 2021, sampling of the ice, using the ice screw method, was also conducted by GEUS during the routine maintenance of the QAS-M, QAS-U (61.1753 N, 46.8195 W, 900 m elevation) and QAS-L (61.0308 N, 46.8493 W, 280 m elevation) weather stations.

In order to collect an ice surface sample, an ice screw (1.5 cm in diameter) was pushed into the ice surface for about 2 cm depth. The ice retrieved was then placed into a 15-ml centrifuge tube. This was repeated 4 times for each sample / tube. Due to the nature of the weathering crust of the ice surface, each ice screw core generated between 2 and 4 ml of sample. Samples collected for algal counting during the Deep Purple ice camp were immediately processed back in the camp using an upright field microscope (VisiScope® 100, Model BL124) with a 100x magnification, while samples collected by GEUS were kept in the refrigerator for < 1 month until processing back in Denmark. No typical preservatives (e.g., glutaraldehyde or paraformaldehyde) were added to the samples this time, since this would require additional health and safety procedures. However, chemical preservation of the samples is strongly recommended in future sample collection.

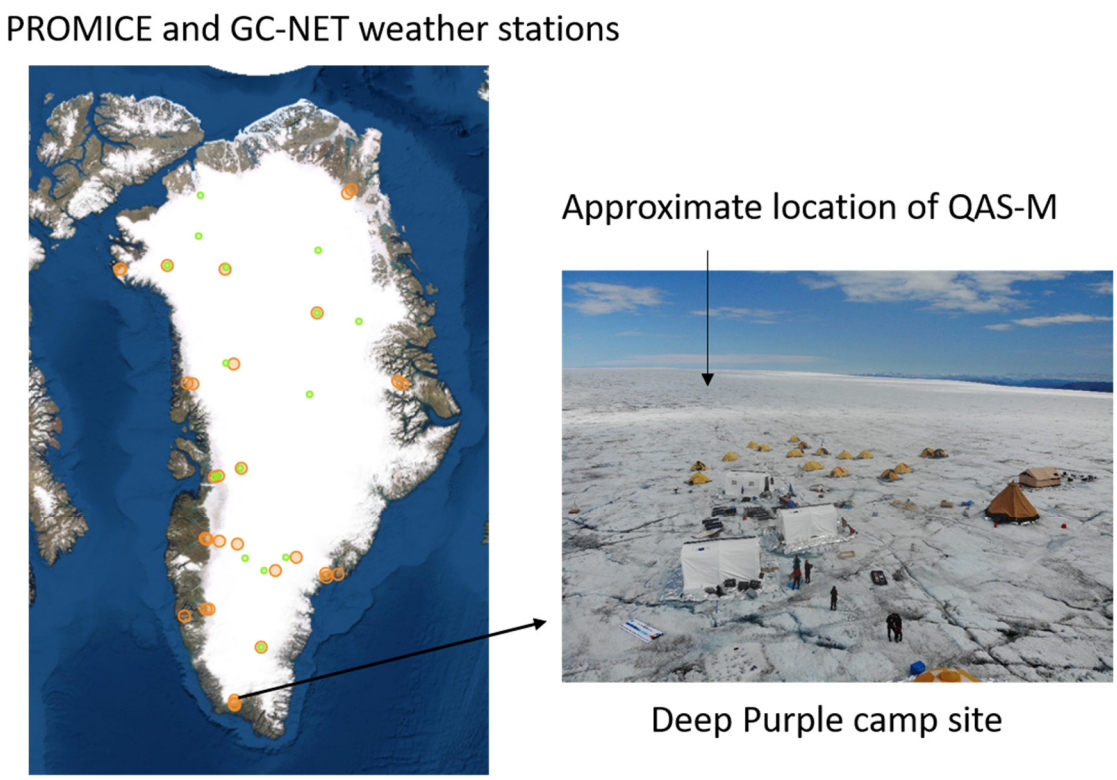

Figure 2.3. Overview of the Deep Purple ERC-Synergy camp in relation to the GEUS QAS-M weather station. The orange circles indicate the PROMICE stations, while the green circles indicate the GC-NET weather stations. The arrow on the left indicate the QAS weather stations in the Narsuarq/Qaqortoq area. There are three weather stations in the area (QAS_L, QAS_M and QAS_U, where L, M and U are low, middle and upper elevation, respectively).

2.3 Sample handling and counting

Counts were performed using a Fuchs-Rosenthal haemocytometer (Lancing, UK) on an inverted microscope with a 100x magnification (Nikon Eclipse Ti), according to Williamson et al. (2018). For those samples containing sufficient cell abundance, a minimum of 100 cells were counted. Three groups of algae were counted separately: the snow algae *Chlamydomonas cf. nivalis* also referred to as *Sanguina nivaloides*, the filamentous glacier ice algae *Ancylonema nordenskiöldii* and the mostly unicellular *Ancylonema alaskana*, formerly known as *Mesotaenium berggrennii* (Figure 2.4). Other biological large organisms (e.g., fungi, cyanobacteria) are also visible, but were not considered in the microscope counts, since their direct impact on albedo is likely minor. Minerals and dark cryoconite material were noted in the samples but not microscopically quantified considering their diversity in size and composition.

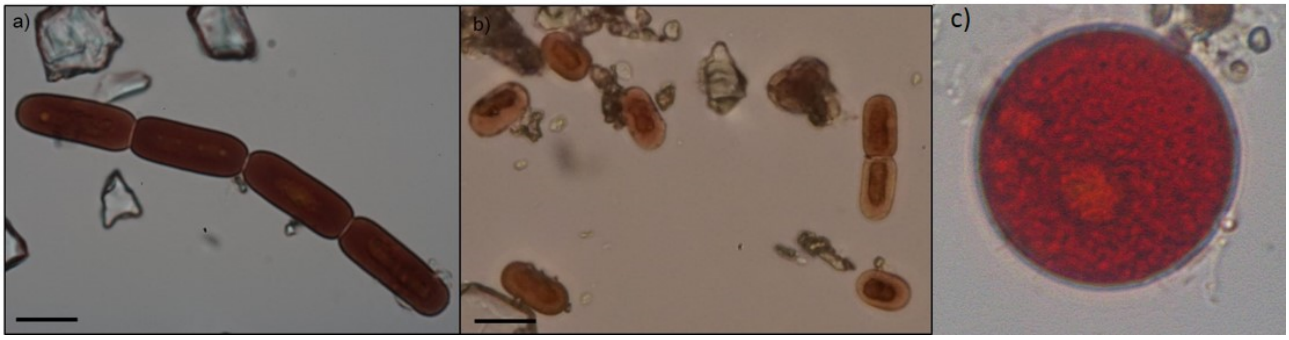

Figure 2.4. Three types of glacier snow and ice algae taken into account for the quantification of the presence of pigmented biological material on ice surfaces. Scale bar in the photos is 10 µm. a) the filamentous glacier ice algae *Ancylonema nordenskiöldii*, b) the unicellular *Ancylonema alaskana*, and c) generic snow algae, which could be a collection of different species, since no genetic analyses are conducted in this project.

2.4 Additional field spectroscopy

Additional field spectroscopy of the ice surface in order to investigate the presence of glacier ice algae signature within the mix of biological and abiotic material. Downward and upward irradiance measurements were collected in the study area between 10 AM and 3 PM under solar zenith angles of 45° to 53° using an ASD FieldSpec4 (Figure 2.5) after Cook et al. (2017) to avoid self-shading from the instrument. Each stored spectrum was the average of 10 measurements. Albedo was computed as the ratio upward to downward irradiance. The spectra were post-corrected for the step at 1000nm (Painter et al., 2001) along with water vapor absorption by polynomial interpolation. Over twenty measurements were conducted around the QAS-M area as part of the fieldwork conducted for the Deep Purple ERC Synergy project. Three representative measurements of ice surfaces are presented in this study: 1) the ice surface just under the radiometer of the PROMICE QAS-M weather station, 2) an ice surface with typical purple coloration, indicative of the presence of glacier ice algae and 3) an ice surface with minimal number of visible impurities.

Figure 2.5. The ASD FieldSpec4 during a measurement of field spectroscopy of a cyoconite hole.

The spectral data were matched with non-invasive microscopy photography using a hand-held microscope (Technaxx, Germany) with a 50x optical magnification. The non-invasive microscopic image was taken exactly at the same location as the field spectroscopy in order to give an overview of the glacier ice algae density associated with the spectral data.

3 Results and discussion

3.1 Sampling evaluation and knowledge transfer to GEUS

While the bespoken sample device – sampling method "a" – developed by the Aarhus University Engineering Department was disregarded from this study already in the planning phase, ice scraping (sampling method "b" in section 2.1) was considered and tested during the Deep Purple ERC-Synergy ice camp campaign. Ice scraping was then dropped due to the number of steps necessary to collect a sample and the time necessary to collect each sample. In order to collect samples with a desired precision in terms of area, a minimum of 20 cm x 20 cm square was necessary to be taken. This procedure takes in average 5-10 minutes per sample and generate a sample volume of ca 500 ml, depending on the nature of the weathering crust. While this volume is appropriate for sampling of parameters such as microbial diversity, pigments, metabolic profiles, it is unnecessarily large for algal quantification.

Sampling with an ice screw (4 x cores within the same tube) generated a volume between 8 and 12 ml into a 15-ml centrifuge tube and was done in 1-2 minutes per sample. The precision in area and depth of the ice surface sampled is acceptable for quantification purposes. The centrifuge tubes were graduated at the 0.5-ml scale, allowing for a rough calculation of the ice density, which is largely variable depending on the weathering crust conditions of the ice surface. The considered volume translated a useful precision by volume (e.g., cells per liter of ice) or roughly by area (cells per m^2). For upscaling exercises and relation between albedo and the presence of biological impurities, expression of cell counts per area is more useful, and thus, incorporation of a more precise method to measure near-surface ice density should be considered. However, for this study, where the main goal is to provide a standard technique for sampling ice surfaces in connection to the maintenance of the PROMICE stations, the results will be expressed below as cells per millimeter of melted surface ice.

To keep the full sampling procedure within 10 minutes for GEUS personnel (i.e., includes label writing on the tubes, decide on sampling locations, taking photos and sampling of material), three single samples were taken for each ground stop. The three samples were divided into three categories. One sample was collected directly under the albedo sensor of the weather station, providing a direct characterization of the ice surface where continuous albedo measurements are available. One sample was taken to represent the average ice surface of the area and one sample was taken to represent a visible dark ice surface area. The samples were taken approximately within 10 m from each other. The last two categories of samples can be the result of a relatively subjective choice and this sampling strategy will need to be further considered in future sampling opportunities. The full procedure was filmed during the Deep Purple ice camp and transferred to GEUS personnel, who successfully sampled the three sample categories in each of the QAS (L, M, and U) weather stations.

In conclusion, after *in situ* methodological tests and literature considerations, the ice screw method for collecting glacier algae was chosen as the most efficient method due to its combined simplicity, speed and reproducibility / precision.

3.2 Glacier snow and ice algal counts

Cell counts for glacier snow and ice algae varied almost two orders of magnitude between different sampling locations, indicating a large heterogeneity in the distribution of biological impurities on the ice surface. Figure 3.1 shows the algal abundance under the radiometer of QAS_M weather station, a representative ice surface and a typical dark / purple ice surface. This is put in comparison with the average counts conducted during the Deep Purple camp ca 500 m from the weather station. In addition to the variability in numbers, most interesting is a large difference in the two main types of glacier ice algae between the locations. The Deep Purple ice camp location was almost exclusively dominated by the filamentous glacier ice algae *Ancylonema nordenskiöldii*, while QAS_M was strongly dominated by the unicellular *Ancylonema alaskana*.

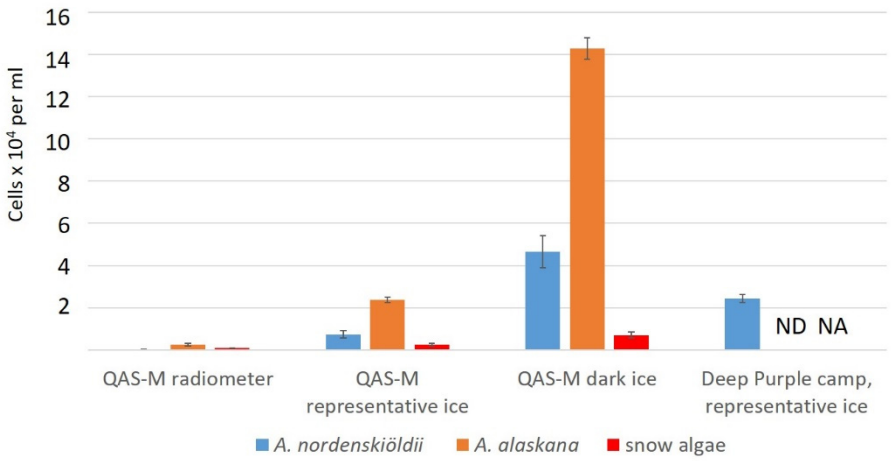

Figure 3.1. Average algal cell counts (± error) from the samples collected by GEUS (QAS_M) in comparison with representative ice samples collected ca 500 m from the QAS_M (Deep Purple camp). ND – not detected and NA – not accounted.

Ice screw samples were also collected at QAS_U and QAS_L, resulting in very different profiles in terms of the presence of biological and abiotic / cryoconite impurities. While the samples at QAS_U were almost entirely dominated by minerals, the ice surface of QAS_L had some more visible biological component (Figure 3.2).

Considering the close proximity to the coast and heavy marine influence of the QAS PROMICE stations, the ice surface contained a relatively large proportion of cryoconite signature observed by both microscopy and from the spectral data. This is very different from other locations further inland on the south-west Greenland ice sheet, such as the K-transect, where most of the darkening is dominated by the presence of glacier ice algae and minerals are relatively translucent (Cook et al., 2020). The proportion of a high load of abiotic / cryoconite impurities as the dominant factor of ice darkening was particularly prominent close to the radiometer of the PROMICE weather stations. This reinforces the importance of having proper characterization of the ice surface conditions across different PROMICE weather station sites before any association between albedo and the presence of both abiotic and biological impurities can be made.

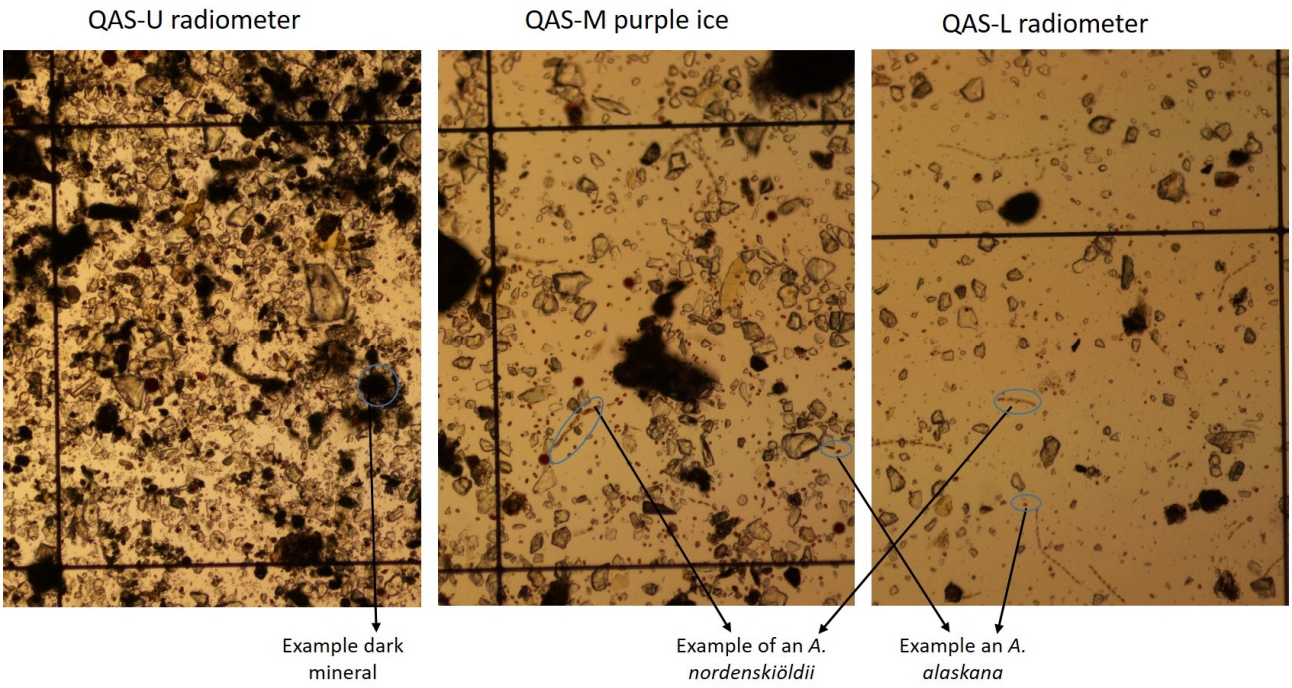

Figure 3.2. Microscopic image at 100x magnification of samples collected at three different PROMICE weather stations with examples of biological and abiotic/cryoconite material observed.

3.3 Spectral albedo coupled with non-invasive microscopic images

Figure 3.3 illustrates an example of three distinct ice surfaces measured by a spectroradiometer with an accompanying microscopic photo over the ice surface. The spectral signal of the dark ice in (b), which is dominated by biological impurities, presents a signature in the visible region that is different to that of the spectral signal from the dark ice surface at the QAS_M PROMICE station (a), notably at the 675 nm wavelength, where the chlorophyll signature from the algae can be observed. The matching microscopic photos also show a much larger presence of biological impurities in the dark ice in (b) compared to the dark ice surface at the weather station (a) and clean ice (c). Thus, both spectroradiometer images and direct microscopy have potential to be used in the future to monitor and distinguish the impact between biological and abiotic impurities on the darkening of the ice surface. Currently, at the PROMICE weather stations, the radiometer is placed ~2.5 m higher than the spectroradiometer (see Figure 3.1), meaning the PROMICE albedo measurement has a larger footprint with more averaging of surface heterogeneity. However, since the PROMICE radiometer only measures a broadband and not a spectral signal, distinguishing between the responsible mechanism for the darkening of the ice surface (i.e., abiotic vs biological impurities) is not possible.

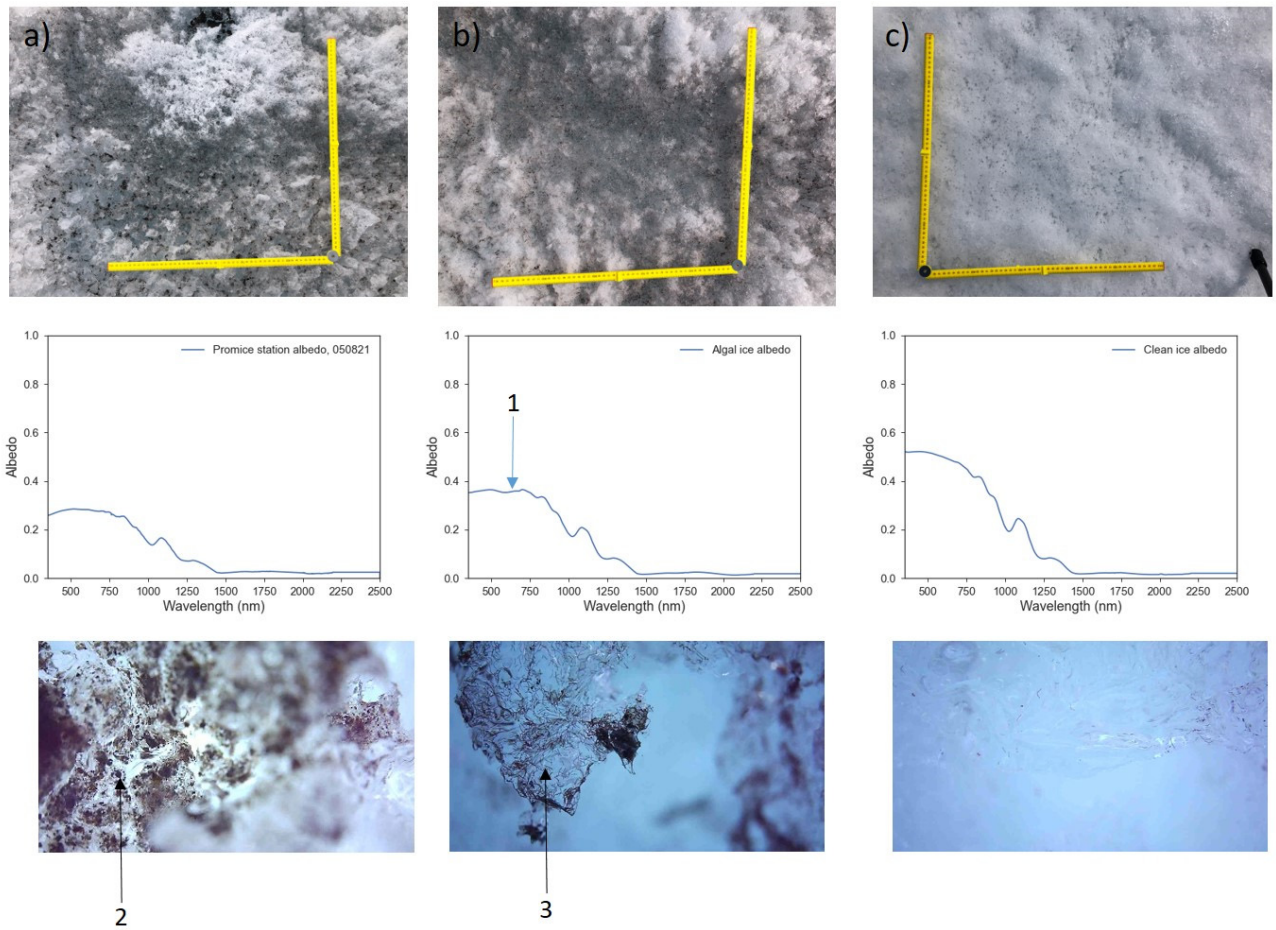

Figure 3.3. Spectral albedo (middle panel) coupled with non-invasive microscopic images (50x magnification, lower panel) from three different types of ice surface (upper panel). a) is the ice surface just below the radiometer of the PROMICE QAS_M station, b) is a typical ice surface with high concentration of glacier ice algae and c) is a clean ice surface for comparison. Arrow (1) indicates the 675 nm wavelength, where the chlorophyll signature from the algae can be observed through a lower albedo. Arrow (2) shows an example of mineral/cryoconite material within the weathering crust of the ice surface. Arrow (3) shows a glacier ice algae that dominates the dark impurities of the weathering crust.

4 Methodological procedure protocol for col-lecting glacier ice algae during future PROMICE/GC-Net weather station maintenance missions

Below is a step-by-step of the methodological procedure suggestion to be incorporated in future maintenance missions of PROMICE weather stations as a direct outcome of the present project. Sampling procedure is based on a 10-minute availability during station maintenance. In comparison to the 2021 sampling, a preservation step is added to the sampling procedure and a slight modification of the sampling replication is recommneded. The procedure and material below are designed for an individual weather station stop, but it can easily be scaled up. A body camera is added to the sampling programme in order to facilitate documentation of sampling and area.

4.1 Material

- Ice screw
- 3 centrifuge tubes
- Gloves
- GoPro camera
- Bottle with paraformaldehyde
- Marker pen
- Waterproof notebook.

4.2 Procedure

- Get the body cam in action attached to the head and document the surroundings (i.e., impressions about the level of darkening, heterogeneity of the ice, weather conditions since this is important to describe the weathering crust).
- Put gloves on before sampling
- Before each sampling location, clean the ice screw by taking a sample in the location, but discarding the first ice sample.
- One single sub-sample is done by pressing the ice screw ca 2 cm into the ice. The ice inside the screw is then released into the centrifuge tube. This should be repeated 4 times for each tube / location.
- Four locations should be sampled (one under the radiometer of the weather station and three random samples in the surroundings). Ensure that the GoPro is capturing each of the sampling location in good level of detail.
- Each tube is labeled according to location (PROMICE weather station) and type of sample (e.g., radiometer, representative ice). Labelling of the tubes can be done in advance to save time on the ice.
- Once back out of the ice at the end of the day, the samples in the tubes will be melted. Make a note of the volume sampled using the grading scale in the centrifuge tubes.
- Using gloves, add equal amount of volume of paraformaldehyde, preferably in outdoor location to avoid the fumes of paraformaldehyde.

- Dispose the glove in a plastic bag and return the bag to Denmark as chemical waste.
- The sample is now ready to be transported back home.

5 Recommendations for additional procedures to monitor biological and abiotic impurities on the Greenland ice sheet

Distinguishing between allochthonous (both old and recent atmospheric and abiotic impurities) and autochthonous (glacier algal growth) is one of the main challenges in our understanding of the darkening of glaciers and ice sheets. The current broadband albedo measurements done at the PROMICE-GC net weather stations cannot distinguish between biological and abiotic impurities. However, proper characterization of the ice surface through direct sampling and/or spectral signal characterization has great potential to supplement the PROMICE measurements. In order to quantify mechanisms, triggers, and feedbacks between biological growth on the ice and albedo, we need concerted efforts and procedures for sampling, handling, processing and analyses of abiotic and biotic impurities.

For a localized understanding of the different roles of allochthonous and autochthonous impurities in particularly areas of Greenland, we recommend monitoring stations that can carry instrumentation specific for the purpose. First, we need to be able to quantify the allochthonous particle delivery rates and fluxes. Second, we need to be able to quantify rates of changes in autotrophic (i.e., glacier ice algae growth) contribution over time. Spectral characterization of the ice surface has a potential to enable distinguishing between abiotic and biotic impurities. The interactions between impurities and the ice surface are, nevertheless, complex and changes of the weathering crust must also be taken into consideration. For instance, a study in the south-west margin of the Greenland ice sheet, demonstrate that the state of the near-surface ice has a similar importance to the darkening of the ice as the abiotic and biological impurities (Tedstone et al., 2020). Naturally, the state of the weathering crust has a strong feedback with the presence and type of impurities, which makes detailed studies of spectral signal of the ice even more relevant.

While this study demonstrates the clear value of having ground-truth data of biological and abiotic impurities for characterization of ice surfaces and validation of albedo measurements, the data alone has some limited value for scaling up the darkening process to larger areas of the Greenland ice sheet. Linking the spectral data from the ground with unmanned aerial vehicle (UAV) and satellite remote sensing offers a promising way to follow biological darkening of the Greenland ice sheet in the recent past, present and future (Figure 5.1). With the advent of various sensors aboard different satellite platforms, the demands of having spatially distributed ground measurements are increasing rapidly. Potential collaboration with the European Space Agency could help the monitoring and analysis of glacier ice algal and various surface processes on the GrIS. The remote sensing derived products (e.g. albedo, chl-a concentration, snow cover) require long-term ground-truth data for developing algorithm and validation. The difference in ground sampling distance of the in-situ measurements and satellite sensors is one of the most challenging issue in the scaling of various remote sensing products. Site selection and the deployment of UAV/rover for better local spatial scale monitoring could help address this issue.

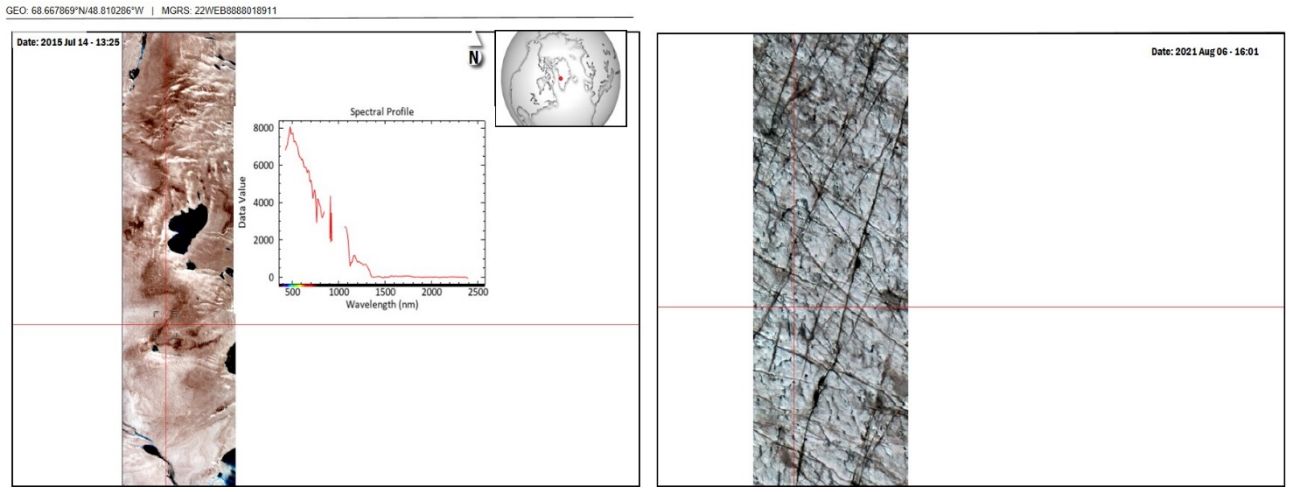

Figure 5.1. Figure on the left shows a strip of hyperspectral image acquired by EO-1 Hyperion Hyperspectral Imager from NASA. The spectral profile of a pixel is shown in the diagram on the right. The surface reflectance values are scaled by 10000. The acquisition of hyperspectral satellite imagery has limited spatial (normally around 30m) and temporal resolution. The use of hyperspectral imaging camera on UAV offers flexibility in capturing the temporal evolution of ice at any desired frequency if weather permits. With the improved spatial resolution (cm scale), we can attribute the contribution of albedo from various target objects (e.g. glacier algae, dust, ice etc.). Figure of the right is the hyperspectral UAV image captured by the microHSI SHARK 310 hyperspectral camera. The ground sampling distance is around 4-20 cm depending on the flight altitude.

In order to optimize the link between ground-truth data and remote satellite, we also recommend accurate empirical measurements of the optical properties of live glacier ice algae and detailed mechanistic understanding of the development of the surface ice. This would reduce the uncertainty in remotely sensed glacier algal cell concentrations and those techniques could be applied on worldwide glaciers.

6 Conclusions

Overall, a direct sampling approach of the ice is not recommended as a way to monitor biological growth on ice surfaces, unless it is done over repeated seasons and with a more robust sampling effort (i.e., a minimum of 10 samples per location are required). Nevertheless, the direct sampling approach at PROMICE weather stations is still an excellent way to characterize the area where local weather data are available. It also provides a baseline for the causes of darkening of the ice at different locations on the Greenland ice sheet, where wealth of weather data are available via PROMICE. **Therefore, this study strongly recommends that direct sampling of the ice surface at different locations on the Greenland ice sheet should continue whenever it is possible**. Future sampling should also consider the possibility for collection of larger samples that can be used for determination of microbial diversity, using next generation sequencing techniques, and chemical characterization of the ice surface, including pigment profiles.

For monitoring of glacier algal growth on the long term, this report makes three recommendations:

1) Single station monitoring with specialized instrumentation that can distinguish between abiotic impurities and glacier ice algae.

2) Research on the optical properties of glacier algae and other light absorbing particles and the sensitivity of the albedo to the development of the underlying ice surface, which allow the accurate link between remote satellite imagery and glacier algal cell concentrations, and the development of mathematical models.

3) Introduce mobile data collection platforms such as UAV and/or rover. This is to improve the spatial coverage of measurements and help the upscaling with satellite observatory data.

7 References

Anesio, A.M. and Cook, J.M. 2022. Assessment of the impact of glacial algae and abiotic impurities on the melting of the Greenland ice sheet. Aarhus University, DCE – Danish Centre for Environment and Energy, 24 pp. Scientific Report No. 481.

Cook, J. M., Hodson, A. J., Gardner, A. S., Flanner, M., Tedstone, A. J., Williamson, C., Irvine-Fynn, T. D. L., Nilsson, J., Bryant, R. and Tranter, M.: Quantifying bioalbedo: A new physically based model and discussion of empirical methods for characterising biological influence on ice and snow albedo, Cryosphere, doi:10.5194/tc-11-2611-2017, 2017.

Cook, J. M., Tedstone, A. J., Williamson, C., McCutcheon, J., Hodson, A. J., Dayal, A., Skiles, M., Hofer, S., Bryant, R., McAree, O., McGonigle, A., Ryan, J., Anesio, A. M., Irvine-Fynn, T. D. L., Hubbard, A., Hanna, E., Flanner, M., Mayanna, S., Benning, L. G., Van As, D., Yallop, M., McQuaid, J. B., Gribbin, T. and Tranter, M.: Glacier algae accelerate melt rates on the south-western Greenland Ice Sheet, Cryosphere, 14(1), doi:10.5194/tc-14-309-2020, 2020.

Holland, A. T., Williamson, C. J., Sgouridis, F., Tedstone, A. J., McCutcheon, J., Cook, J. M., Poniecka, E., Yallop, M. L., Tranter, M. and Anesio, A. M.: Dissolved organic nutrients dominate melting surface ice of the Dark Zone (Greenland Ice Sheet), Biogeosciences, 16(16), doi:10.5194/bg-16-3283-2019, 2019.

Lutz, S., Anesio, A. M., Field, K. and Benning, L. G.: Integrated "Omics", targeted metabolite and single-cell analyses of arctic snow algae functionality and adaptability, Front. Microbiol., 6(NOV), doi:10.3389/fmicb.2015.01323, 2015.

Lutz, S., Anesio, A. M., Raiswell, R., Edwards, A., Newton, R. J., Gill, F. and Benning, L. G.: The biogeography of red snow microbiomes and their role in melting arctic glaciers, Nat. Commun., 7, doi:10.1038/ncomms11968, 2016.

Nicholes, M. J., Williamson, C. J., Tranter, M., Holland, A., Poniecka, E., Yallop, M. L., Anesio, A., Poniecka, E., Benning, L., McQuaid, J., Lutz, S., McCutcheon, J., Hodson, A., Hanna, E., Irvine-Fynn, T., Cook, J., Bamber, J., Tedstone, A., Box, J. and Stibal, M.: Bacterial dynamics in supraglacial habitats of the Greenland ice sheet, Front. Microbiol., 10(JUL), doi:10.3389/fmicb.2019.01366, 2019.

Painter, T. H., Duval, B., Thomas, W. H., Mendez, M., Heintzelman, S. and Dozier, J.: Detection and Quantification of Snow Algae with an Airborne Imaging Spectrometer, Appl. Environ. Microbiol., 67(3–12), 5267–5272, doi:10.1128/AEM.67.11.5267-5272.2001, 2001.

Perini, L., Gostinčar, C., Anesio, A. M., Williamson, C., Tranter, M. and Gunde-Cimerman, N.: Darkening of the Greenland ice sheet: Fungal abundance and diversity are associated with algal bloom, Front. Microbiol., doi:10.3389/fmicb.2019.00557, 2019.

Stibal, M., Box, J. E., Cameron, K. A., Langen, P. L., Yallop, M. L., Mottram, R. H., Khan, A. L., Molotch, N. P., Chrismas, N. A. M., Calì Quaglia, F., Remias, D., Smeets, C. J. P. P., van den Broeke, M. R., Ryan, J. C., Hubbard, A., Tranter, M., van As, D. and Ahlstrøm, A. P.: Algae Drive Enhanced Darkening of Bare Ice on the Greenland Ice Sheet, Geophys. Res. Lett., doi:10.1002/2017GL075958, 2017.

Tedstone, A. J., Bamber, J. L., Cook, J. M., Williamson, C. J., Fettweis, X., Hodson, A. J. and Tranter, M.: Dark ice dynamics of the south-west Greenland Ice Sheet, Cryosphere, doi:10.5194/tc-11-2491-2017, 2017.

Tedstone, A. J., Cook, J. M., Williamson, C. J., Hofer, S., McCutcheon, J., Irvine-Fynn, T., Gribbin, T. and Tranter, M.: Algal growth and weathering crust state drive variability in western Greenland Ice Sheet ice albedo, Cryosphere, 14(2), 521–538, doi:10.5194/TC-14-521-2020, 2020.

Williamson, C. J., Anesio, A. M., Cook, J., Tedstone, A., Poniecka, E., Holland, A., Fagan, D., Tranter, M. and Yallop, M. L.: Ice algal bloom development on the surface of the Greenland Ice Sheet, FEMS Microbiol. Ecol., 94(3), doi:10.1093/femsec/fiy025, 2018.

Williamson, C. J., Cook, J., Tedstone, A., Yallop, M., McCutcheon, J., Poniecka, E., Campbell, D., Irvine-Fynn, T., McQuaid, J., Tranter, M., Perkins, R. and Anesio, A.: Algal photophysiology drives darkening and melt of the Greenland Ice Sheet, Proc. Natl. Acad. Sci. U. S. A. doi:10.1073/pnas.1918412117, 2020.

Yallop, M. L., Anesio, A. M., Perkins, R. G., Cook, J., Telling, J., Fagan, D., MacFarlane, J., Stibal, M., Barker, G., Bellas, C., Hodson, A., Tranter, M., Wadham, J. and Roberts, N. W.: Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland ice sheet, ISME J., 6(12), doi:10.1038/ismej.2012.107, 2012.

MONITORING GLACIAL ALGAE AND IMPURITIES ON THE GREENLAND ICE SHEET

This project initiated a pilot study for sampling biological growth, alongside the Programme for monitoring the Greenland ice sheet (PROMICE) to better understand the interplay between climatic factors and physical, chemical and biological processes that contribute to surface melting of the ice sheet. The results in the project show that direct sampling of ice surfaces during PROMICE missions provide important information to characterize the surface darkening where local weather data are available.

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