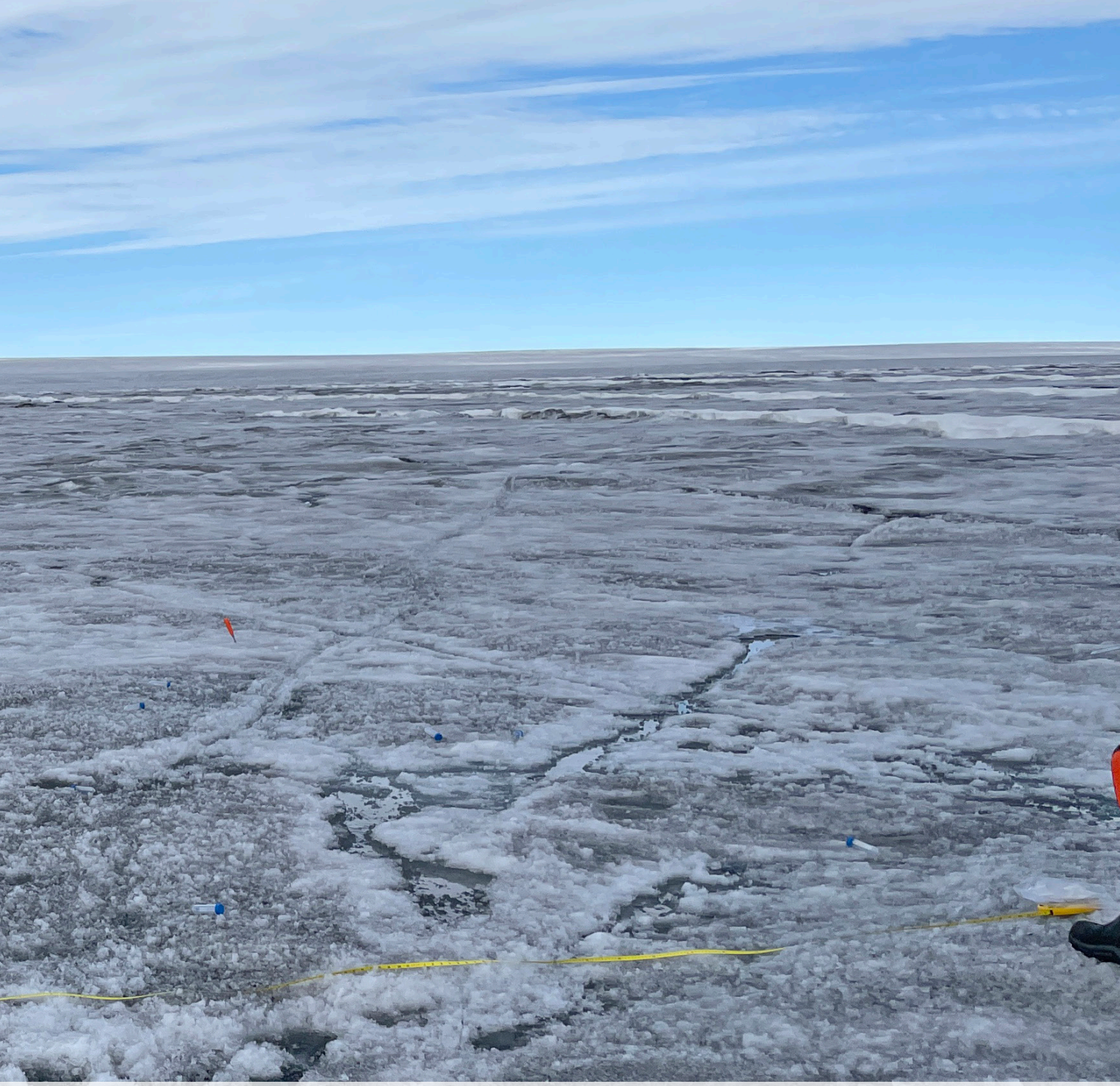

PROMBIO – PROGRAMME FOR MONITORING BIOLOGICAL IMPURITIES ON THE GREENLAND ICE SHEET

Accompanying notes and figures for the 2024 campaign

Technical Report from DCE – Danish Centre for Environment and Energy No. 352 2025

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Data sheet

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Abstract: This report summarizes pigmented algal abundance at PROMICE and GC-Net weather stations that are maintained by the Geological Survey of Denmark and Greenland (GEUS). Key findings include the importance of bare ice duration in controlling glacier ice algae abundance, the need for a minimum of 10 samples from a 50 m² grid for robust statistical representation, and the influence of weathering crust changes on impurity distribution. The presence of pigmented snow algae cysts on the ice surface also contribute to the darkening of the ice and, therefore, should be considered in future studies. The current report emphasizes a randomized sampling approach and increased sampling efforts on PROMICE and GC-Net weather stations, necessitating additional helicopter time for the advanced sample collection.

Keywords:	Greenland ice sheet, albedo, ice darkening, snow algae, ice algae
Front page photo:	Example of a sampling grid at the QAS transect (PROMICE) showing representative dark ice on the Greenland ice sheet.
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Contents

Preface

This report outlines notes, figures and analyses of biological impurities around a selected number of PROMICE and GC-Net automatic weather stations on the Greenland ice sheet of samples collected during the summer of 2024. This is the second year in which samples were collected of glacier ice algae on the ice sheet as part of a monitoring programme. In 2024, PROMBIO aimed to conduct a randomized and more detailed sampling of one of the PROMICE weather stations transect, the QAS transect, in order to characterize in detail one of the dark regions of the ice sheet. Furthermore, samples were also collected at the TAS-A and KAN-L weather stations. Poor weather conditions during the summer 2024 fieldwork limited the fieldwork at the other PROMICE and GC-Net weather stations. In conjunction with data from 2023, this report provides a basis of ground-truth data for validation of remote satellite and future modelling work on estimation of biological and abiotic impurities on the ice sheet. While this report presents an overview of the data, the full dataset can be obtained in the archival 'dataverse' database at the PROMICE and GC-Net webpage (https://dataverse.geus.dk/dataset.xhtml?persistentId=doi:10.22008/FK2/D0JC0P).

Sammenfatning

PROMBIO er et overvågningsprogram for biologiske urenheder på Grønlands indlandsis (GrIS), som udnytter, at de Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS) i forvejen har vedligeholdelsesaktiviteter ved PROMICE- og GC-Net-vejrstationer. I PROMBIO indsamles og analyseres prøver af isoverfladen for at forstå de biologiske faktorer, der bidrager til isens mørkfarvning og afsmeltning. PROMBIO's metode til indsamling af urenheder blev implementeret i 2023 og 2024 og afslørede regionale variationer i bidragene fra abiotiske og biologiske urenheder til isens mørkfarvning. Denne rapport opsummerer forekomsten af pigmenterede alger ved PROMICE's vejrstationer, med uddybende prøvetagning udført ved en af stationerne. Undersøgelserne belyser bl.a. betydningen af varigheden af bar is for forekomsten af gletsjeris-alger, og hvordan ændringer i isforvitringsskorpe påvirker fordelingen af urenheder. Desuden understreger undersøgelserne behovet for mindst 10 prøver fra et 50 m² gitter for nøjagtig repræsentation af algerne. Tilstedeværelsen af pigmenterede snealgecyster på isoverfladen bidrager også til isens mørkfarvning og bør derfor være en del af fremtidige undersøgelser. Den aktuelle rapport fremhæver behovet for en randomiseret prøvetagningsmetode og øget prøvetagningsindsats PROMICE- og GC-Net-vejrstationer, hvilket kræver ekstra helikoptertid til prøveindsamling. Fortsat overvågning er afgørende for at skaffe data til klimamodeller og politiske beslutninger.

Summary

PROMBIO is a monitoring program for biological impurities on the Greenland ice sheet (GrIS), leveraging the maintenance activities of PROMICE and GC-Net weather stations by the Geological Survey of Denmark and Greenland (GEUS). The program collects and analyzes ice surface samples for algal cell density to understand the biological factors contributing to ice darkening and melting. Initiated in 2021, PROMBIO's methodology for gathering impurities was implemented in 2023 and 2024, revealing regional variations in the contributions of abiotic and biological impurities to ice darkening. This report summarizes pigmented algal abundance at PROMICE weather stations, with in-depth sampling conducted in one of the weather stations. Key findings include the importance of bare ice duration in controlling glacier ice algae abundance, the need for a minimum of 10 samples from a 50 m² grid for robust statistical representation, and the influence of weathering crust changes on impurity distribution. The presence of pigmented snow algae cysts on the ice surface also contribute to the darkening of the ice and, therefore, should be considered in future studies. The current report emphasizes a randomized sampling approach and increased sampling efforts on PROMICE and GC-Net weather stations, necessitating additional helicopter time for the advanced sample collection. Continued monitoring is essential for informing climate models and policy decisions.

1 Introduction and context

PROMBIO is a programme for monitoring biological impurities on the Greenland ice sheet (GrIS) that takes advantage of activities related to the maintenance of PROMICE and GC-Net weather stations by the Geological Survey of Denmark and Greenland (GEUS) to collect samples of the ice surface. Those samples are then analysed for algal cell density, providing ground truth information of the biological potential in the darkening of the ice. Current knowledge indicates that a combination of physical, geochemical and biological factors contributes to ice surface darkening, which accelerates to melting (Benning et al., 2014; Cook et al., 2017, 2020; Lutz et al., 2016, 2018; Williamson et al., 2018, 2020). Predictive melt models need to be able to distinguish between the different factors darkening the ice and PROMBIO provides the opportunity to characterize the ice in diverse locations on the Greenland ice sheet.

In 2021, PROMBIO devised the methodology for gathering various impurities, including biological samples, from the surface ice (Anesio et al 2022) and this methodology was implemented in 2023 (Anesio 2024) and 2024 (current report). In 2023, PROMBIO acquired samples across 10 weather stations spanning 4 different regions on the GrIS. The resulting data demonstrated that different regions of the GrIS have variable relative contributions to the darkening of the ice between abiotic and biological impurities (Anesio 2024). Furthermore, the data from 2023 points to the need for a more thorough sampling coverage for characterizing better the ice surface in each different region, considering the heterogeneity of both abiotic and biological impurity distribution on the ice surface. Thus, the current version of PROMBIO, presented in this report, puts into practice a randomized sampling approach and additional sampling effort of one region of the GrIS: the QAS-transect of the PROMICE and GC-Net Programme. For such characterization to occur, additional helicopter time is needed for collection of samples.

The ERC Synergy project, DEEP PURPLE (https://www.deeppurple-ercsyg.eu/home), has provided since 2020 crucial mechanistic understanding about biological, chemical, and physical processes associated with the ice surface melting of the Greenland ice sheet (GrIS), along with some in-depth ground truth data of biological impurities on the ice. Glacial ice and snow algae are heavily pigmented, which in turn, darkens the surface considerably (Stibal et al., 2017; Williamson et al., 2020; Yallop et al., 2012; Chevrollier et al., 2023). Two fundamental results in the past years underpin the necessity to monitor and characterize the bare ice surface of the GrIS to a larger extent, which has been the goal of PROMBIO. First, DEEP PURPLE has demonstrated that biological growth on the ice is not limited by nutrients and it is very likely that biological darkening of the ice will continue inland on the GrIS as climate becomes warmer (Halbach et al., 2025). Second, the combined data from DEEP PURPLE and PROMBIO indicate that the duration of bare ice is a critical factor in the abundance of darkening impurities, and different regions of the Greenland ice sheet exhibit varying primary mechanisms for darkening (Anesio, 2024, Feng et al., 2024). These findings underscore the complexity of factors driving ice darkening and highlight the need for continued monitoring to inform climate models and policy decisions. The combined fundamental research and monitoring programme presented here will increase the certainty of the predictions of the GrIS melt that can be used in the Intergovernmental Panel on Climate Change.

2 Fieldwork and procedures

PROMBIO sampling procedures in 2024 have taken into account the recommendations from the international consortium CASP-ICE (Cryospheric Algal Sampling Protocols International Collaboration and Exchange - https://microlabbristol.org/casp-ice/). CASP-ICE is an international network of researchers working on snow and glacier algae across the cryosphere. The network aims to align efforts across the research community to standardize protocols on the sampling and monitoring of snow and glacier algal blooms in the cryosphere globally. Alignment of protocols between PROMBIO and CASP-ICE will facilitate inter comparisons of biological impurities between the Greenland ice sheet and glaciers worldwide.

Two sampling approaches were conducted during the 2024 campaign. One which was carried out by GEUS personnel during the maintenance of PROMICE and GC-Net weather stations TAS-A and KAN-L, and one in which in-depth sampling was carried out by Aarhus University personnel alongside GEUS during the maintenance of the QAS-transect weather stations (Fig. 2.1).

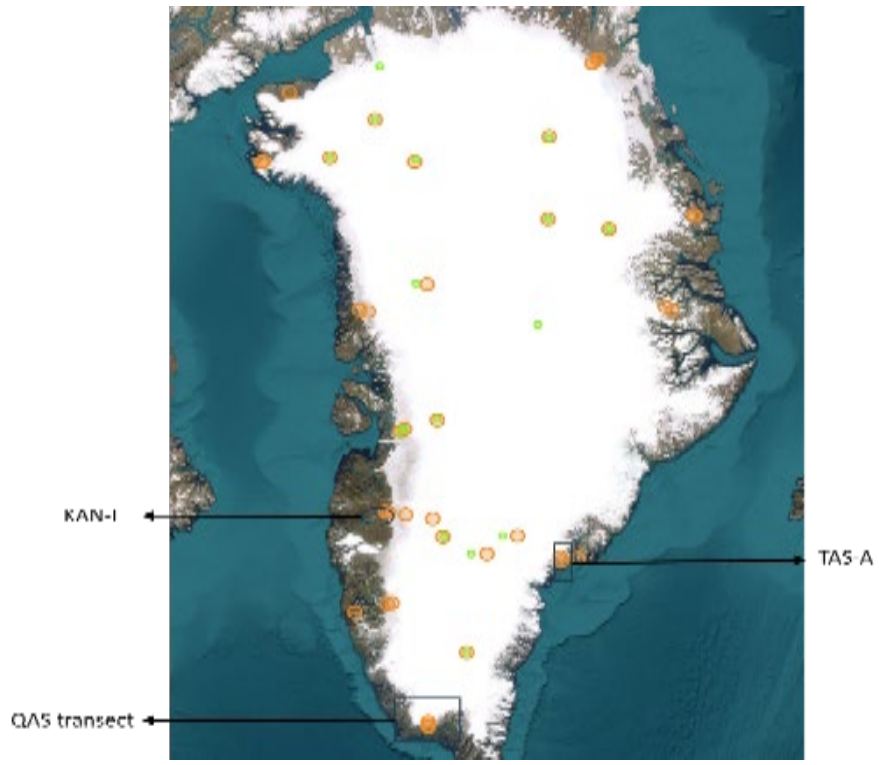


Figure 2.1. The PROMICE/GC-NET (orange) and old GC-NET (green) stations, and the three locations, TAS-A, KAN-L and QAS, where samples were taken by PROMICE-GC-Net during the 2024 summer field season.

For TAS-A and KAN-L, three types of samples were collected using an ice screw, as previously used in PROMBIO to collect the top 2 cm of the ice surface. One type was collected under the radiometer of the weather station, which can then be directly associated to albedo measurements by the weather station. One sample represented the "average" ice in the vicinity of the weather station, while another sample was collected for dark ice. The samples

were preserved with acetic lugol before transport back to a laboratory at Aarhus University (Risø campus). Lugol preservation was used instead of paraformaldehyde, because preservation with paraformaldehyde results in loss of pigmentation in glacier ice algae and lugol is currently the recommended preservative by CASP-ICE.

For the QAS-transect, in-depth sampling was carried out using two different methods: the ice screw, as described above and using a chisel to cut a square of 2.5 cm x 2.5 cm with a 2 cm depth (Fig. 2.2). At least 5 samples were collected under each of the radiometers at QAS-L, QAS-M and QAS-U weather stations. Furthermore, random samples (between 20 and 25, depending on time availability) were collected near each of the weather stations at QAS-L, QAS-M and QAS-U within a 7 m x 7 m grid. All samples were preserved with acetic lugol.

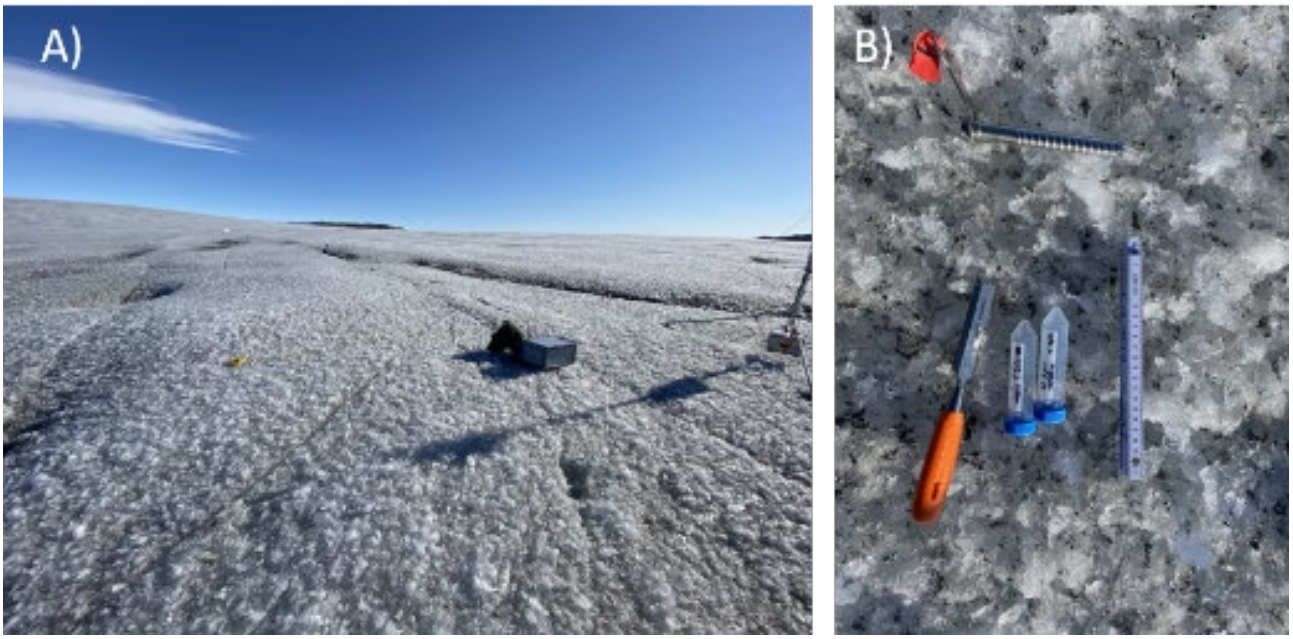


Figure 2.2. A) Example of the 50 m2 representative grid sampled (QAS-L). Between 20 and 25 samples were randomly sampled in the grid. B) Example of the aspect of the weathering crust sampled by both a chisel and ice screw.

The preserved samples were counted using a hemocytometer under an Olympus microscope, alternating between 200 and 400x magnification, depending on the size of the cells. A total of 2 µl were counted per sample. Therefore, the limit of detection of biological impurities is considered to be 500 cells per ml in this study. Abiotic loading (presence of minerals) was qualitatively classified between low, medium and high.

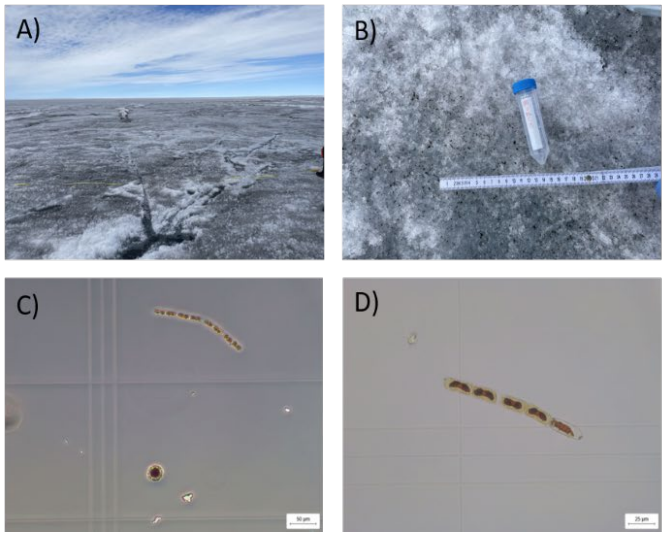
3 Results

Table 3.1 presents the main results for the PROMBIO 2024 sampling, as average, minimum and maximum biological impurity load of algal cells ml^{-1}. The complete version of the table, with counting for each sample, is also available as a Dataverse file at the PROMICE portal, containing links to photos when available at different scales (Anesio et al., 2025). Figure 3.1 provides an example of how images at different scales are associated to numerical data of cells counts for each individual sample.

Table 3.1. Summary of the results of biological and abiotic impurities of samples collected for PROMBIO in 2024. The average number of cells include both glacial ice and snow algae. N is the number of samples collected. The table uses similar parameters for easy comparison with previous PROMBIO data (Anesio 2024).

date	Location	site	Average (cells/ml)	Standard deviation (cells/ml)	N	Min (cells/ml)	Max (cells/ml)	Approx. abiotic load*
27-08-2024	QAS-U	Radiometer	1630	1490	5	0	3750	Medium-high
27-08-2024	QAS-U	Randomized sampling	26300	24200	23	0	87200	Medium-high
01-09-2024	QAS-M	Radiometer	7260	7850	9	0	18800	Medium
01-09-2024	QAS-M	Randomized sampling	45400	72900	19	0	303000	Medium
01-09-2024	QAS-L	Radiometer	18900	347000	10	15600	1160000	Medium-high
01-09-2024	QAS-L	Randomized sampling	83700	82600	25	20300	401000	Medium-high
09-09-2024	TAS-A	Radiometer	938	1290	5	0	2500	Low
09-09-2024	TAS-A	Representative ice	21100	25800	5	0	54100	Low-medium
09-09-2024	TAS-A	Dark ice	1500	407	5	1250	2190	Medium-high
23-08-2024	KAN-L	Radiometer	0	NA	1	NA	NA	Low
23-08-2024	KAN-L	Representative ice	0	NA	1	NA	NA	Low
23-08-2024	KAN-L	Dark ice	14100	NA	1	NA	NA	Low

* Abiotic load – semi-quantitative indication whether abiotic impurity (mineral) loading is low, medium or high.
NA – information not available



E)

Ice algae	Snow algae	Minerals	observations
Cells/ml	Cells/ml		
12200	1560	Rich in minerals	Many cells in chains

Figure 3.1. Images at different scales during sampling of PROMBIO. A) Overview of the 50 m2 grid sampled near the QAS-U weather station. B) Closer look at the weathering crust of one of the 20 samples collected within the grid. C and D) Examples of microscopic images from the same sample collected in B). C) has representatives of both snow algae and filamentous ice algae. E) Information on algae and minerals obtained from sample B).

The increased sampling effort in 2024 for the QAS-transect and TAS-A, compared to previous years, provides a more statistically robust reflection of the heterogeneity of the distribution of impurities on the ice surface. Therefore, inter-annual comparisons should be done with care. For instance, the increased sampling effort at QAS-U (N = 25-30 samples), compared to previous years (N = 1-3 samples), reveal a far better understanding of the distribution of biological impurities on the ice surface at higher altitudes, showing, with higher confidence, that glacier ice and snow algae are also present in significant numbers at higher altitudes. The positive correlation between bare ice duration and biological impurities (space for time substitution) in the QAS-transect, shown in PROMBIO in previous years, is nevertheless, still observed despite the different sampling efforts (Fig 3.2). Interestingly, the contribution of snow to the total algal community has positive trend with bare ice duration. This suggests that attention should be given to biological processes in snow in areas where snow is present for longer periods during the summer melt season. Resting stages of snow algae are also heavily pigmented and have the potential to accelerate snow melt.

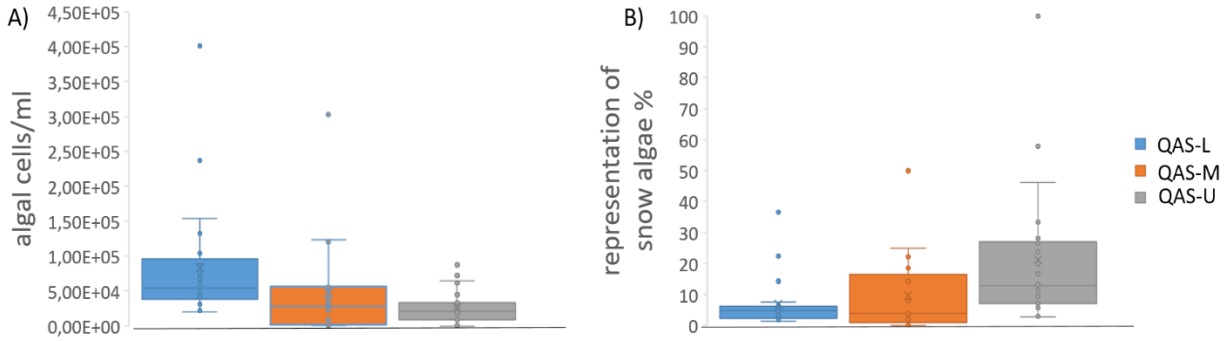


Figure 3.2. A) Box-plot showing the total cell numbers (sum of ice and snow algae) distribution in the QAS transect. QAS-L is at the lowest elevation, while QAS-U is at the highest elevation. B) Proportion of the snow algae relative to the total algal community (in %). The data are all from the randomized grid.

Comparisons between samples collected under the radiometer and randomized samples collected in the same region reveal that albedo data from the weather stations may not always be representative of the region they are placed (Fig. 3.3). We propose that the ground truth data provided by PROMBIO can be used for correcting albedo observations from the weather station in future scaling up and modelling applications.

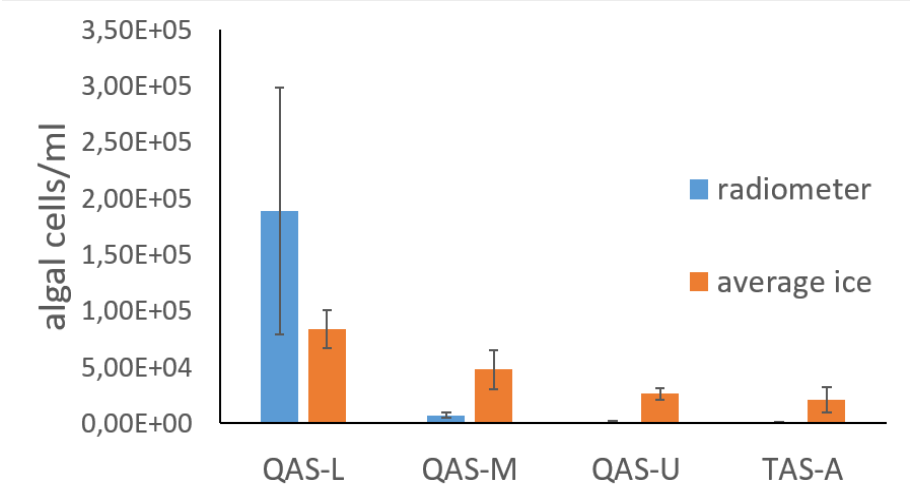


Figure 3.3. Total cell numbers (sum of ice and snow algae) comparison between sampling under the weather station radiometer and average ice in the same area at different PROMICE weather stations. The data demonstrate that care should be taken when using information from the weat

4 Discussion and use of the data

This report provides a basic summary of pigmented algal abundance at the surface of the ice around PROMICE weather stations, collected at the end of the summer of 2024. In this phase of PROMBIO, an in-depth sampling was conducted for the QAS-transect. We recommend that this report is read in conjunction with previous reporting from PROMBIO (Anesio, 2024) and with the full dataset publicly available at the GEUS 'dataverse' (Anesio et al., 2025). Below are a few notes that are worthwhile considering when using the full dataset for remote satellite validation and modelling work.

a) *The comprehensive data collection at the QAS transect confirms that the bare ice duration is an important control of the abundance of glacier ice algae*

We have previously argued that bare ice duration over the melt season is a good predictor of dark ice (Anesio, 2024, Feng et al., 2024). Using the randomized sampling approach in the QAS-transect, we conform this assertion with higher confidence. The in-depth sampling over the grid also demonstrates better the presence of ice and snow algae at higher altitudes of the QAS-transect, which was not observed before with one-single sample approach.

b) *How many samples should be collected from a randomized grid?*

Based on the in-depth sampling procedure in the QAS-transect, we suggest that a minimum of 10 samples should be collected from a representative 50 m^2 grid. Distribution of algae on ice surfaces can be relatively heterogeneous. Therefore, a moderate level of precision needs to be balanced between available time to collect samples and minimal acceptable margin of error. A recent study on mapping of red algal blooms in snowfields argue for multiple small and distributed samples to be more representative of snow algal abundances than fewer and larger samples (Chevrollier et al., 2025). Figure 4.1 gives two examples from the QAS-transect of algal abundance ± error for increasingly number of samples. Considering the heterogeneity in darkening and algal distribution and practical purposes, 10 samples of representative ice would provide an average abundance estimation with a 35% coefficient variation at 75% confidence level. In order to achieve an average abundance estimation with 30% coefficient variation (which is relatively acceptable for microscopy work) at 95% confidence level, then the number of samples recommended is ca 40, which is not practical, considering the amount of time available for maintenance work.

c) *It is important to collect samples both under the radiometer of the PROMICE weather stations and representative ice surface in the same region*

Based on the differences in algal abundances between surface collected just by the weather station and nearby the weather station, we recommend that corrections may need to be applied if historical albedo data from the PROMICE weather stations are used for modelling and upscaling purposes.

d) *Changes in the weathering crust aspect during the summer need to be carefully considered in future validation work between remote sensing data and the different factors that can cause ice darkening*

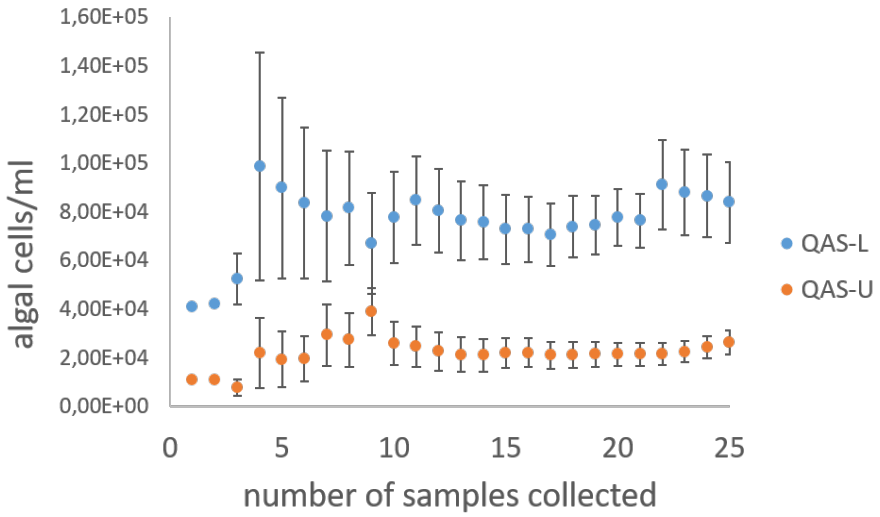


Figure 4.1. Examples from the QAS-transect of algal abundance ± error over an increasing number of samples. Samples collected with a chisel within a representative 50m^2 grid

We would like to stress that most maintenance and sampling work around the PROMICE weather stations and PROMBIO sampling has been conducted towards the end of the summer, where re-freezing and melting of the weathering crust can substantially influence distribution of impurities at the surface of the ice. We noticed from many of the photos taken during the sampling that the weathering crust at the end of the season is more reflective, while darker ice is more common at the peak of the summer.

e) Pigmented snow algae cysts can survive throughout the summer and contribute to darkening of the ice

Samples collected for PROMBIO 2024 were analysed this time for both ice and snow algae. We have observed that most of our samples contained a fraction of snow algae varying between 0 and 100% (average of 14 ± 18%) of the total pigmented algal community. Even if the contribution of snow algae to ice darkening, compared to ice algae, can be small (Halbach et al., 2022), the presence of snow algae in PROMBIO samples is a good indication that snow algal blooms were present in the sampling area during the spring. It is well known that snow algal blooms can result in faster melt of snow (Di Mauro et al., 2024; Chevrollier at al., 2025), which in turn, can lead to earlier bare ice exposure during the melting season. We propose that, PROMBIO data in the future should keep aiming to distinguish between snow and ice algae to optimize use of biological data to establish the impact of algae on the darkening of both ice and snow.

5 Conclusions and recommendations

Based on the results of PROMBIO data from 2024, we provide the following conclusions and recommendations:

- Whenever possible, additional samples should be collected to increase statistical robustness and understanding of the spatial variability at the sampling location. The aim should be 10 random samples as a minimum.

- Sample preservation with acetic lugol, instead of paraformaldehyde, substantially improved visualization of algal cells during later microscopy work.

- We recommend that future PROMBIO missions continue distinguishing between snow and ice algae in order to optimize data utilization and predictions of both ice and snow melting driven by biological impurities.

- Future PROMBIO missions should focus in additional areas to increase in-depth characterization of biological and abiotic particles on ice and snow on the Greenland ice sheet. In-depth characterization could be particularly useful if sampling is conducted during the peak of the summer, where the ice is darkest.

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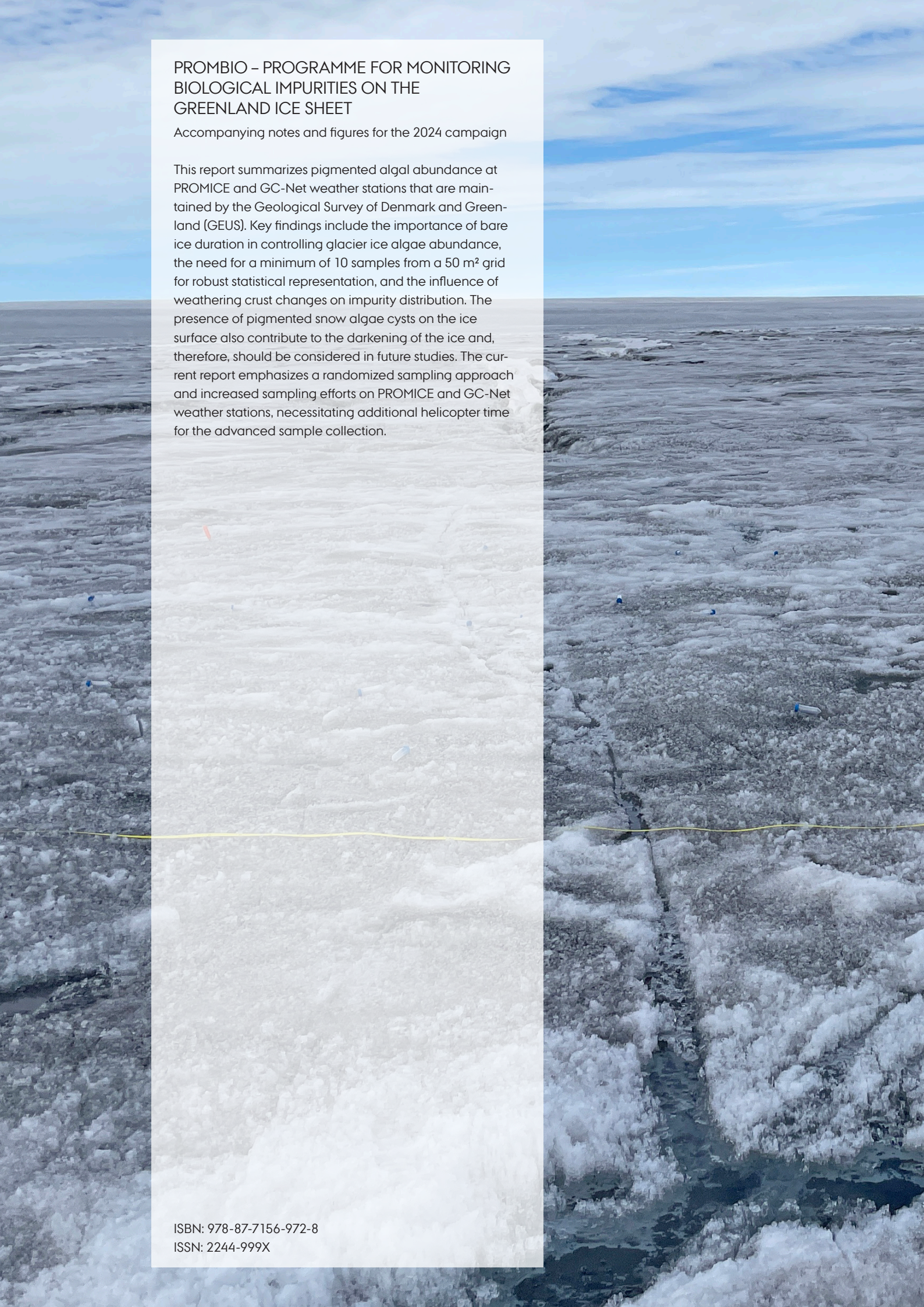

PROMBIO – PROGRAMME FOR MONITORING BIOLOGICAL IMPURITIES ON THE GREENLAND ICE SHEET

Accompanying notes and figures for the 2024 campaign

This report summarizes pigmented algal abundance at PROMICE and GC-Net weather stations that are maintained by the Geological Survey of Denmark and Greenland (GEUS). Key findings include the importance of bare ice duration in controlling glacier ice algae abundance, the need for a minimum of 10 samples from a 50 m² grid for robust statistical representation, and the influence of weathering crust changes on impurity distribution. The presence of pigmented snow algae cysts on the ice surface also contribute to the darkening of the ice and, therefore, should be considered in future studies. The current report emphasizes a randomized sampling approach and increased sampling efforts on PROMICE and GC-Net weather stations, necessitating additional helicopter time for the advanced sample collection.

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