ASSESSMENT OF THE IMPACT OF GLACIAL ALGAE AND ABIOTIC IMPURITIES ON THE MELTING OF THE GREENLAND ICE SHEET

Scientific Report from DCE – Danish Centre for Environment and Energy No. 481 2022

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Preface

Contrary to expectations, glaciers and ice sheets are teeming with microbial life and are now widely recognized as one of the Earth's biomes. One of those organisms, specialized in growing on ice surfaces, is a type of microscopic plant that is heavily purple-brown pigmented and is significantly darkening the ice surface of the Western and Southern parts of the Greenland ice sheet. This is now recognized as a major contributor of ice melting. This report is intended to provide a short analysis to policy makers of the current understanding of the impact of biological and abiotic impurities on the melting of the Greenland ice sheet.

This report is funded by a grant from the Klimastøtten til Arktis to Anesio for the project "PROMBIO – Programme for monitoring of biological and abiotic impurities on the Greenland ice sheet". Anesio and Cook are also partially 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). Deep Purple puts together an international team of scientists to investigate the physical and microbial processes that darken the Greenland Ice Sheet and accelerate sea level rise.

Sammenfatning

Global opvarmning fører til et betydeligt tab af ismasse fra gletsjere rundt om i verden, og smeltningen af Grønlands indlandsis (GrIS) er en særlig trussel mod kystsamfundene. De seneste målinger peger på, at GrIS alene er ansvarlig for en væsentlig del af havniveaustigningen. Det meste istab sker langs den sydlige og vestlige rand af GrIS, hvilket falder sammen med et stort mørkt område på isoverfladen. Jo mørkere isen er, jo mere stråling absorberes, hvilket genererer varme og mere afsmeltning. I første omgang spekulerede forskere i, at høje koncentrationer af gammelt støv, der smeltede ud af isen, og øget atmosfærisk aflejring af sort- eller brunkul var hovedårsagerne til, at isen blev mørkere. Men det er nu velkendt, at lokale biologiske faktorer har en meget relevant påvirkning. Mikroskopiske planter, specialiseret i og som kan trives på isoverflader (gletsjeris-alger), udgør den dominerende mørkfarvnings- (og dermed smelteforøgende) komponent i indlandsisen i det vestlige Grønland. Baseret på nuværende viden om gletsjeris-algers biologi er det højst sandsynligt, at isalgeopblomstring (og dermed mørkfarvning af is) vil stige som en konsekvens af den globale opvarmning og derfor bør tages i betragtning ved estimering af ismassetab i fremtiden.

Summary

Global warming is leading to considerable loss of ice mass from glaciers worldwide and the melting of the Greenland Ice Sheet (GrIS) is a particular threat to coastal communities. The most current measurements indicate that the GrIS alone is responsible for a significant part of sea level rise. Most ice loss occurs along the southern and western margins of the GrIS, which coincides with a large dark area on the surface of the ice. The darker the ice gets, the more radiation is absorbed, generating heat and more melt. Initially, researchers speculated that high concentrations of old dust melting out of the ice and increased atmospheric deposition of black or brown carbon were the main cause of the darkening of the ice. However, it is now well recognized that local biological factors have a much relevant impact. Microscopic plants, specialized and able to thrive on ice surfaces (glacier ice algae), are the dominant darkening (and thus, melt enhancing) component of the western Greenland ice sheet. Based on the current knowledge of the biology of glacier ice algae, we suggest ice algal blooms (and thus ice darkening) are likely to increase as a consequence of climate warming and should be taken into account in the estimations of ice mass loss in the future.

1 Glaciers and ice sheets are the most under investigated biome on Earth

Glaciers and ice sheets were long believed to be sterile environments, but just like other large ecosystems (e.g., tropical forests, tundra), they are now known to be teeming with life (Anesio et al., 2017; Anesio and Laybourn-Parry, 2012). This biome is also the most under-investigated on the planet from a biological perspective, representing a new and exciting frontier in science (Figure 1.1). Home to large, naturally occurring communities of microbes, glaciers and ice sheets host unique metabolically active organisms, interacting with each other. These processes represent more than just a minor curiosity of life under extreme conditions. On glacier surfaces, microbes have been shown to alter physical and chemical characteristics of snow and ice with direct consequences for snow/ice solar-heating and amplified melt (Cook et al., 2020; Stibal et al., 2017; Williamson et al., 2020). Under the ice, in subglacial habitats, microbial communities contribute to substantial amounts of greenhouse gases to the atmosphere, and they also add to the delivery of downstream nutrients and turbidity (Sharp and Tranter, 2017).

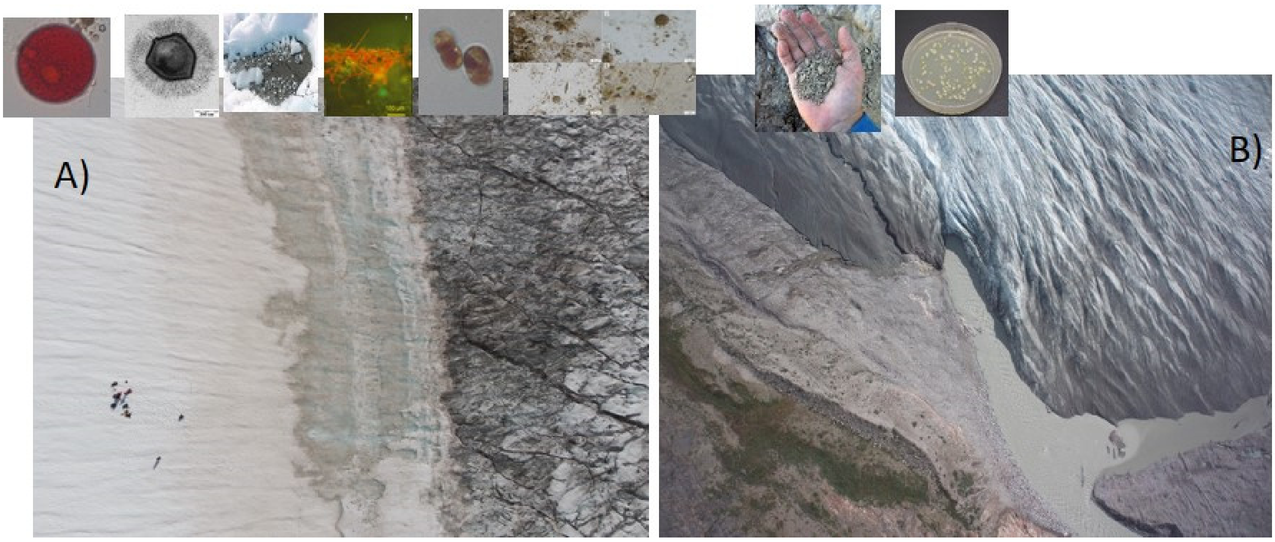

Figure 1.1. The glacier biome and some of its habitats and organisms through the lens of drones and microscopy. A) drone imagery of the interface between snow and bare ice zone of the Mittivakkat glacier in East Greenland, showing the transition between white and red snow, slush and dark ice. They are all colonized by active microbial communities. Microbial pictures on the top of the image (A) from left to right show red snow algae, giant virus, cryoconite hole, cryoconite granules colonized by cyanobacteria, pigmented glacier ice algae and chytridiomycota associated with glacier ice algae. B) drone imagery of the outflow of the Leveret glacier in West Greenland, showing runoff, mostly from subglacial origin, with high concentrations of solutes and turbidity. Pictures on the top of the image (B) are glacial flour, culture of bacteria from subglacial samples.

2 The Greenland ice sheet is getting darker and this leads to more melting

Melting of the Greenland Ice Sheet (GrIS) is a threat to coastal communities worldwide (Anon, 2006). Sea level would rise by 7.2 m if the GrIS is fully melted (Bamber et al., 2001). The most current measurements indicate that the GrIS alone was responsible for 10.8 ± 0.9 millimeters of sea level rise between 1982 and 2018 (Shepherd et al., 2020). This contribution has increased during the past 10-15 years. Most ice mass loss occurs along the southern and western margins of the ice sheet (Bamber et al., 2012).

Ice albedo (Greek for ‘whiteness’), which is a measure of proportion of the incident light or radiation that is reflected by the ice surface, is the strongest control on the melt generated at the surface of the ice sheet for a given climate (He et al., 2013; Masson-Delmotte et al., 2018). The darker the ice gets, the lower the albedo is, which in turn means that the ice is absorbing more radiation, generating heat and more melt (Figure 2.1). The surface albedo in the western margin of GrIS declined from 1996-2012 by 0.02 per decade (Van Den Broeke et al., 2009), and this is a significant driver of melting in the region (Rignot et al., 2011) (Figure 2.2).

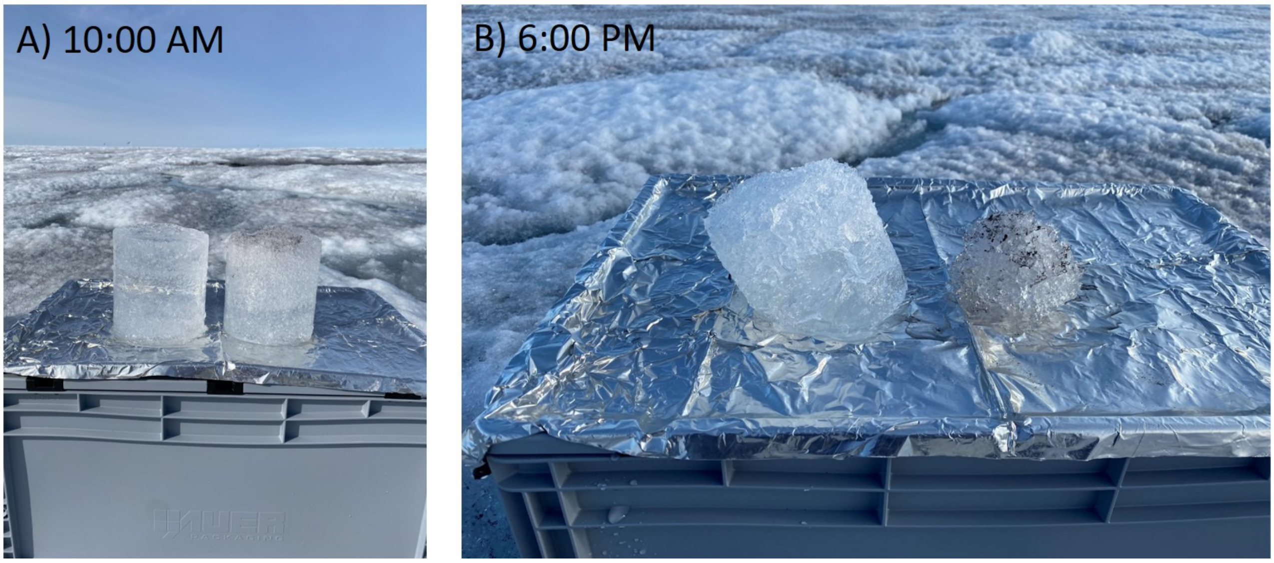

Figure 2.1. Empirical demonstration of the impact of impurities in the melt of ice. A) shows a photo of two ice cores of similar size but with different amounts of impurities on its surface freshly cut at 10am on the Greenland ice sheet. B) shows a photo of the same cores at 6pm after a fully sunny day. Photos: Alexandre Anesio

Since the demonstration that the Western margins of the GrIS are becoming darker, some researchers initially speculated high concentrations of old dust melting out of the ice (Wientjes et al., 2011; Wientjes and Oerlemans, 2010) and increased atmospheric deposition of black or brown carbon (e.g., 17) were the main cause of the darkening of the ice. Currently, it is now well recognized that local biological factors have a relevant impact (Cook et al., 2020; Ryan et al., 2018).

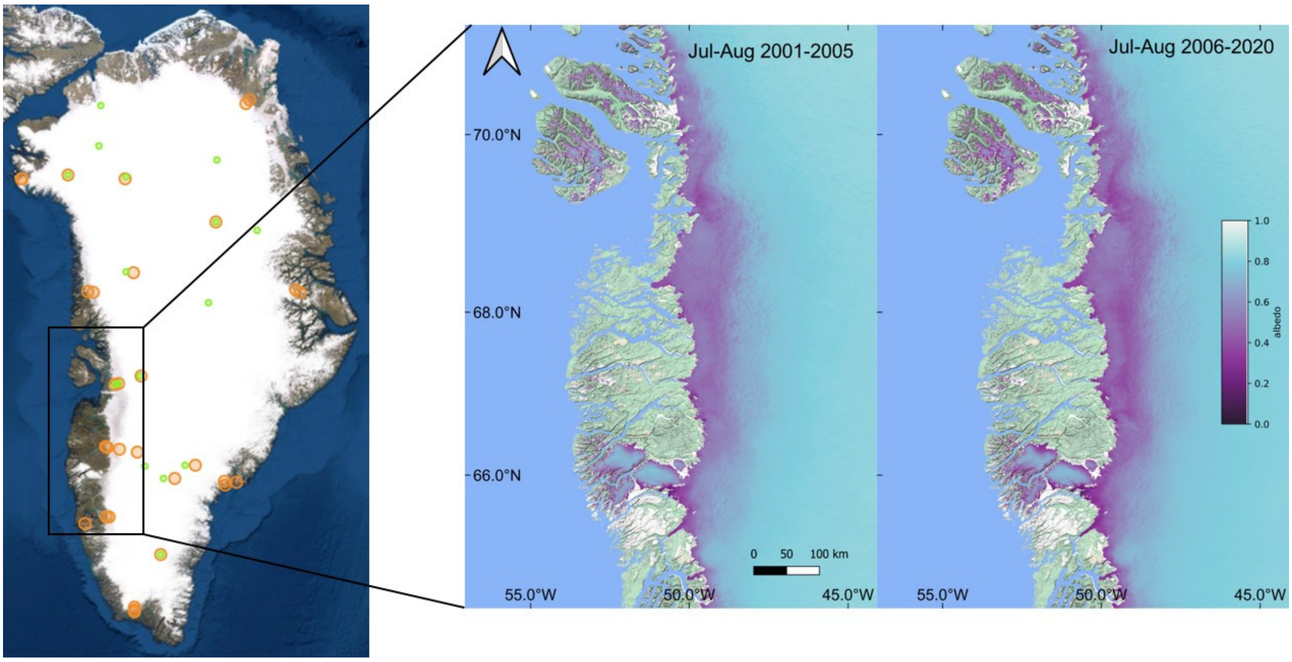

Figure 2.2. Zoom in of the GrIS dark zone showing average albedo between July and August at two different time spans (title of each map). The dark zone is substantially darker in the last period (2006-2020). The albedo maps are created by Shunan Feng from the Department of Environmental Science – Aarhus University.

3 Microscopic plants are greatly responsible for the darkening of the ice

Glacier ice algae (Figure 3.1) are the dominant darkening (and thus, melt enhancing) component of the western Greenland ice sheet. The glacier ice algae community is dominated by two species: the filamentous *Ancylonema nordenskiöldii* and the mostly unicellular *Ancylonema alaskana*, formerly known as *Mesotaenium berggrennii* (Procházková et al., 2021). The impact of glacier ice is not only observed in the GrIS, but on worldwide glaciers, including the European Alps, Antarctica, Svalbard and Himalayas (Ling and Seppelt, 1986; Di Mauro et al., 2020; Takeuchi, 2013; Takeuchi et al., 2019; Yoshimura et al., 1997).

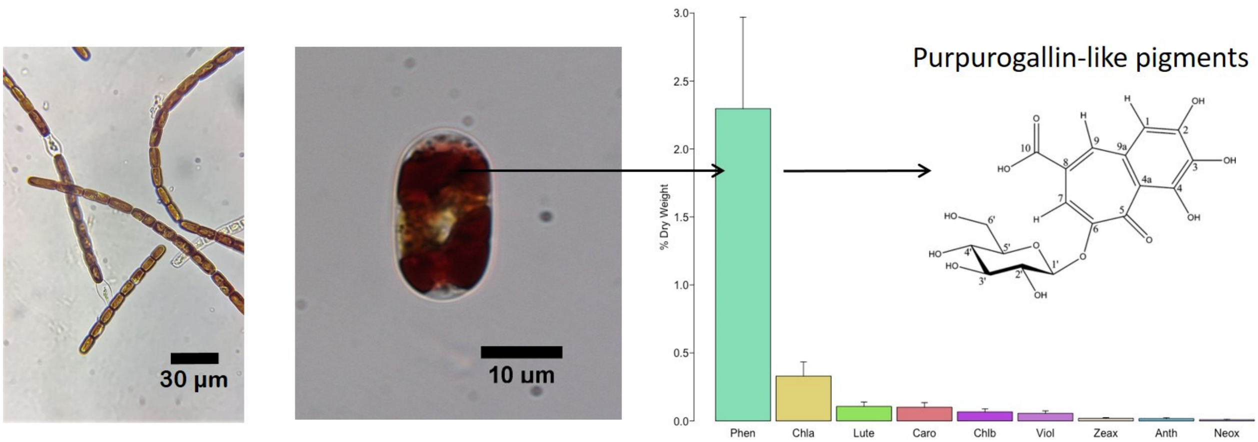

Figure 3.1. Different types of glacier ice algae and their main pigment. From left to right: the filamentous *Ancylonema nordenskiöldii* (Photo: Alexandre Anesio), the single cell *Ancylonema alaskana* (photo: Laura Halbach) and a graph with the different proportions of pigments within a glacier ice algae showing that the purpurogallin-like pigment (Phen) is the main pigment in the algae (data in the graph is from Williamson et al. (2020). The purpurogallin-like pigments is the main cause of why the ice looks purple-brown.

In the Western parts of the GrIS, glacier ice algae are in concentrations of 100,000 – 100,000,000 cells per litre (Stibal et al., 2017). The ice algae contain a unique deep purple pigment, purpurogallin, which is used primarily as a protection against the high incidence of UV radiation on ice surfaces (Williamson et al., 2020; Yallop et al., 2012). This dark pigmentation is also the responsible factor which darkens the ice surface considerably (Williamson et al., 2020).

The separation between the impact of minerals and biological components on the darkening of the ice can be challenging because they are often mixed and sometimes similar in color and therefore hard to isolate in optical measurements. Cook et al. (2020) provided one of the first comparisons of the contributions of local mineral dust and glacier ice algae. They used a suite of empirical, theoretical and remote-sensing data to quantify and map algal contributions to melting on the south-western GrIS. Cook et al. (2020) found that glacier algae alone (and without counting their indirect effects) can cause an ice albedo reduction ca 20x higher than mineral dust.

Controls on ice surface albedo also include the physical configuration of the ice, the type, concentration and compositional variations of light absorbing particles (LAP) that include black carbon, mineral dust, and, crucially, biological particulates (Box et al., 2012; Cook et al., 2020; Stibal et al., 2017).

Scaling up studies of glacier ice algae impact: Biological growth of icebound algal cells can accumulate biomass high enough to cause total albedo reduction between 12% and 21%, depending on the algal cell abundances. In the south-western zone of the GrIS only, this could mean that glacier ice algae is responsible for between 4.4 and 6.0 Gt of runoff in a cold year (e.g., 2017) and between 8.8 and 12.2 Gt in a warm year (e.g., 2016) (Cook et al., 2020).

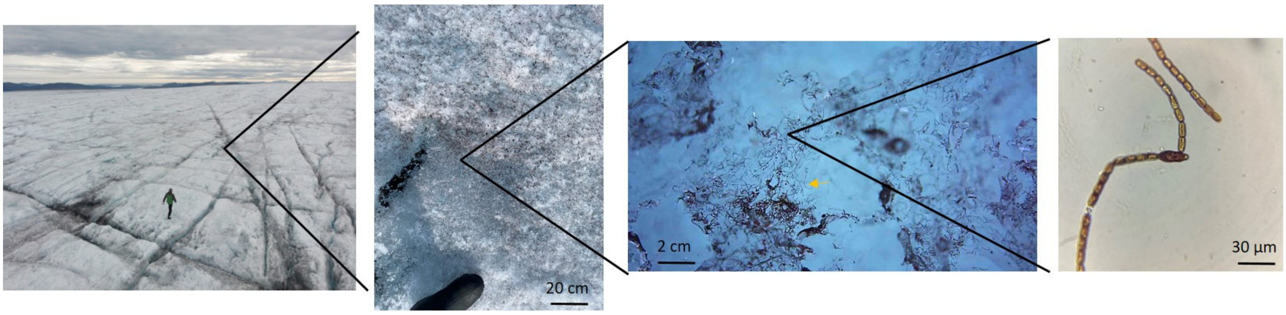

Figure 3.2. A zoom of dark patches of ice from drone to the microscopic scale. From left to right: a drone image of the ice surface at the south of the Greenland ice sheet at the beginning of the glacier ice algal bloom onset (photo: Ate Hendrik-Jan Jaarsma), a photo of the ice aspect taken from about 1.70 m from the ground (photo: Alexandre Anesio), a photo taken of a grain of ice with a 50x magnification microscope – the yellow arrow indicates a filamentous glacier ice algae (photo: Alexandre Anesio) and a photo of the filamentous glacier ice algae taken with a microscope using 100x magnification (photo: Laura Perini).

In a historical context, the IPCC AR4 report in 2007 makes already strong mention that during the 20th century, glaciers and ice caps have experienced widespread mass losses and have contributed to sea level rise. There is also established evidence changes in albedo is an important part of mass loss in addition to increasingly global temperatures. At that time, the IPCC report flags at low level of scientific understanding on the issue, but points to black carbon aerosols deposited on snow as important components surface albedo reduction. The upcoming IPCC report (information in draft report) will add more certainty that darkening of the ice is a significant driver of ice mass loss. Algae growing on the ice, black carbon and dust are all mentioned as the reason for recent albedo changes in the Greenland ice sheet. The belief that black carbon is causing albedo decline is on the basis of relatively few, reliable direct measurements of black carbon. There is still uncertainty about the different roles of biology and particulate minerals and the interplay between them, despite the recent evidence that biology is probably the most relevant driver of darkening.

4 The biology of glacier ice algae and its relevance to melting of glaciers

4.1 Nutrient requirements: Where do glacier ice algae get their nutrients from?

All biological entities need nutrients to survive and this is not different in the glacier ice algae. Current knowledge of the nutrient requirements in glacier ice algae is still scarce. Carbon, nitrogen and phosphorus are the major elements that are part of the composition of organisms. Since glacier ice algae are microscopic plants and, as such, can perform photosynthesis, they can fix CO_2 from the atmosphere. Therefore, carbon is not a limiting nutrient for them. However, nitrogen and phosphorus are speculated to be limiting in glacial and ice sheet environments. Snowmelt may be the main nitrogen input to the ice surface environments (Hodson et al., 2005; Holland et al., 2019). In most freshwater aquatic ecosystems, phosphorus is the limiting nutrient and the expectation is that the same is true for glacial surfaces. In a recent study, a direct link between mineral phosphorus in surface ice and glacier ice algae biomass could be observed across the southwest melting zone of the ice sheet (McCutcheon et al., 2021). This means that even if mineral dust is not the main cause in albedo reduction on the Western sector of the GrIS, the associated phosphorus sourced from the dust likely drive glacier ice algal growth, leading then to the decrease in albedo indirectly. On the other hand, another recent study has demonstrated that the nitrogen and phosphorus requirements of glacier ice algae can be very low, in fact, much lower relative to the nutrient requirements of other algae and plants (Williamson et al., 2021). If the latter assertion is confirmed, this means that glacier ice algae may not be as nutrient limited as presently believed.

The big research question, considering the current warming climate conditions, is whether glacier ice algae can grow in the cleaner ice that will be melting out at the surface of the ice sheet away from the margins of the GrIS. Even relatively low ice algal concentrations (~100,000 – 1,000,000 cells per liter) result in decreases in surface albedo of ~0.2, whereas high algal loads (~100,000,000 cells per liter) cause depression of albedo by up to 0.6 (Cook et al., 2020). These are big numbers, considering that albedo varies between 0 and 1. Changes of this magnitude clearly have a major impact on surface mass balance and melting, and the potential growth of ice algae across wider regions of the ice sheet requires urgent attention now, if the melt regime of the GrIS in future is to be predicted with confidence. Considering the potential low nutrient requirements for glacier ice algae, the nutrients released from the ice melt should be enough to sustain formation of ice algae blooms, once the extension of bare-ice areas increase as a consequence of climate warming.

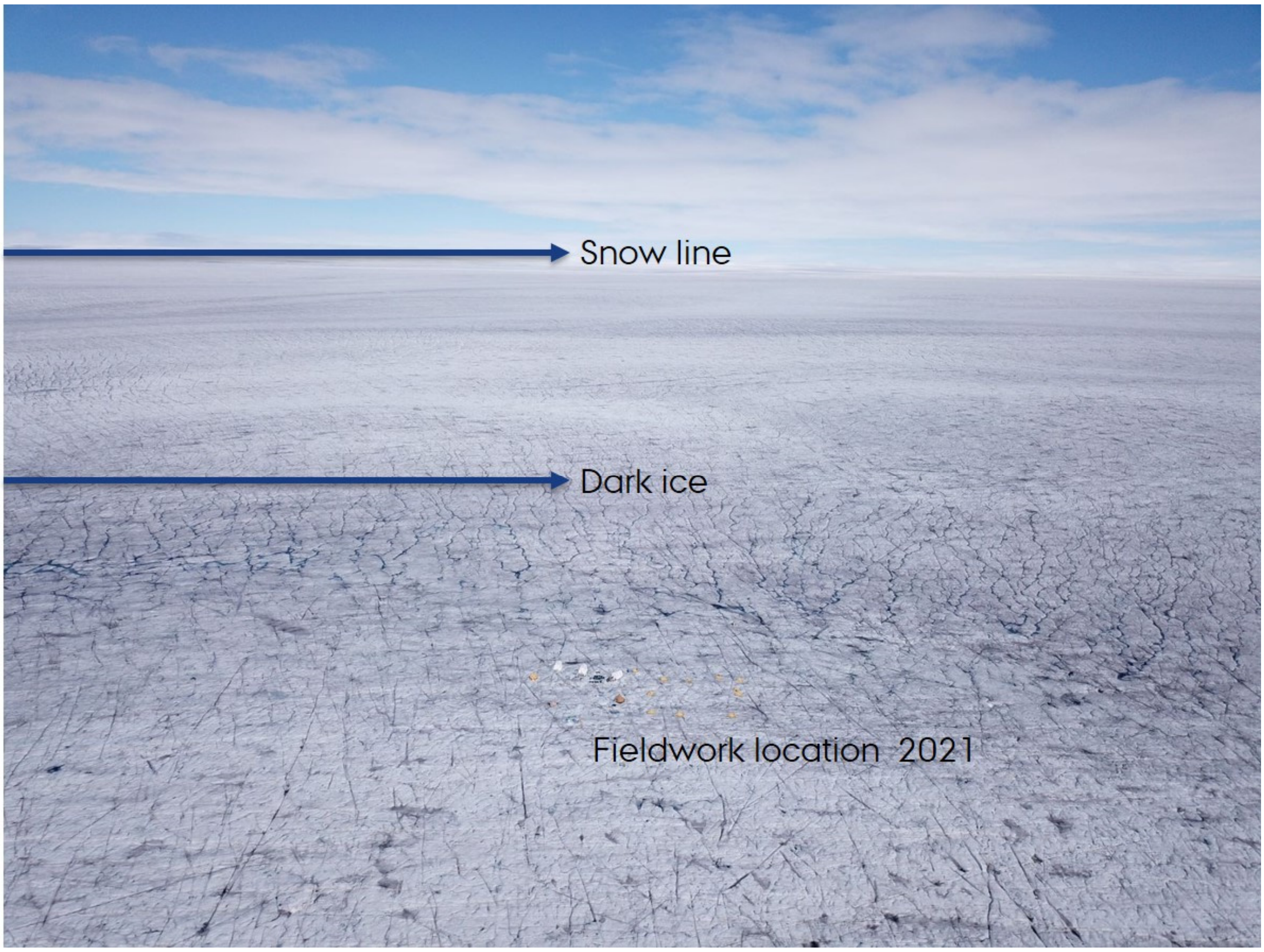

Figure 4.1. Landscape view of the ERC Deep Purple camping in the south of the Greenland ice sheet during the 2021 field-work season. The photo shows the dark area of the ice that is heavily colonized by glacier ice algae and the snow white line further up on the ice sheet. If future results confirm that the glacier ice algae nutrient requirements is low, then there is a strong possibility that the white areas will be colonized by glacier ice algae in the future. Photo: Shunan Feng.

4.2 Pigments of the ice sheet surface

The glacier ice algae possess large amounts of protective pigmentation, including large quantities of a unique purpurogallin phenolic pigment, purpurogallin carboxylic acid-6-O-β-D-glucopyranosidel (Figure 3.1). In addition of giving the algae protection against UV radiation, this is potentially an important mechanism to generate heat and liquid water surround the cell (Williamson et al., 2020). The purpurogallin pigment is arguably the main cause why the glacier ice algae is so important in the darkening of the ice surface. The brown-purple-colored purpurogallin absorbs broadly across the near UV and visible wavelength range (λmax 338 nm; (Remias et al., 2012a, 2012b)) and may exceed Chlorophyll *a* (Chl *a*) concentrations by an order of magnitude ((Williamson et al., 2020), figure 3.1).

Knowledge of the pigment concentrations and distribution in both snow and glacier ice algae and how they can be used for interpreting satellite imagery could be a promising tool to investigate the changes in algae biomass that may lead to additional darkening and melting of the GrIS and other glaciers worldwide. Direct measurements of glacier ice algae numbers and biomass are challenging to make and they do not allow for spatial and temporal upscaling very easily. Therefore, a few attempts have been conducted to link the spectral characteristics of the glacier ice algae with satellite imagery. Wang et al. (2018)

used the reflectance ratios between 709- and 673-nm bands in Sentinel-3 imagery to characterize the spatial pattern of algal abundance. Similar "band ratio" techniques were also employed by Di Mauro et al. (2020) in the European Alps. Cook et al. (2020) also used a machine-learning technique applied to Sentinel-2 data to map glacier algae in a 10,000 km^2 area of the south-western GrIS. However, accurate quantification of cell concentrations at the scale of the whole GrIS melt-zone remains a challenging research goal, mostly due to uncertainty in 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. Therefore, accurate empirical measurements of the optical properties of live glacier algae and detailed mechanistic understanding of the development of the surface ice are required to reduce the uncertainty in remotely sensed glacier algal cell concentrations. By doing so, these studies will certainly be able to demonstrate the growth of algae (and thus darkening) on sections of the Western GrIS and smaller glaciers.

4.3 Controls of glacier ice algae: What keeps them in check?

Glaciers and ice sheets do not only have unique species of dark pigmented algae, but they also have communities of fungi, bacteria and viruses that are unique to the glacier biome (Anesio et al., 2007; Bellas et al., 2015; Perini et al., 2019). Those microbial communities interact with each other and some species may stimulate algal growth, while others may act as controls of growth. Currently knowledge about biological controls of glacier algae biomass is extremely scarce. There is recent evidence (Fiołka et al., 2021) that a specific group of fungi (Chytrids) are present on glacier surfaces worldwide and they are seen in close association with glacier ice and snow algae (Figure 4.2). Chytrids are known to act as parasites of algae and animals, but they can also be opportunistic decomposers. It is important to note that it is not known yet whether Chytrids on the surface of glaciers act as parasites, controlling glacier algal blooms or whether they are opportunistic decomposers (i.e., taking advantage of nutrients released from already dead algae).

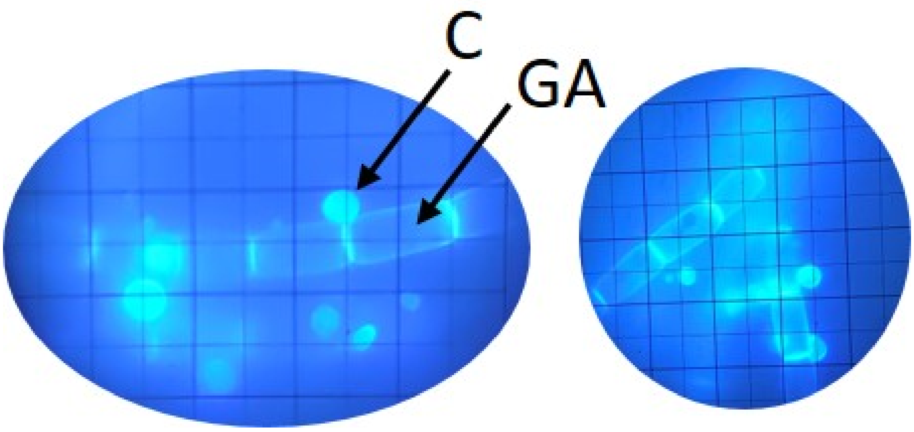

Figure 4.2. A sample from the dark ice collected in south of the GrIS and stained with calcofluor white. "C" indicates a Chytrid interacting with a glacier ice algae (GA). Photo: Laura Perini

Viruses are also known to control biological processes in nature. On glaciers, unique viruses that infect bacteria are ample observed and they are also active (Bellas et al., 2013). However, currently there is no knowledge of whether there are viruses that could potentially infect glacier ice and snow algae.

An additional potential control of glacier algae biomass, which is related to a potential physical limitation is rain. This could provide an important feedback mechanism between climate change, glacier ice algae abundance and albedo. Stibal et al. (2017) demonstrated that glacier ice algae numbers are reduced after rain events. The ERC Deep Purple project has also found a strong redistribution of cells on the ice surface after rain events (Figure 4.3) that might be associated with cells being washed from the ice crystals. This is an area of research that needs far more understanding.

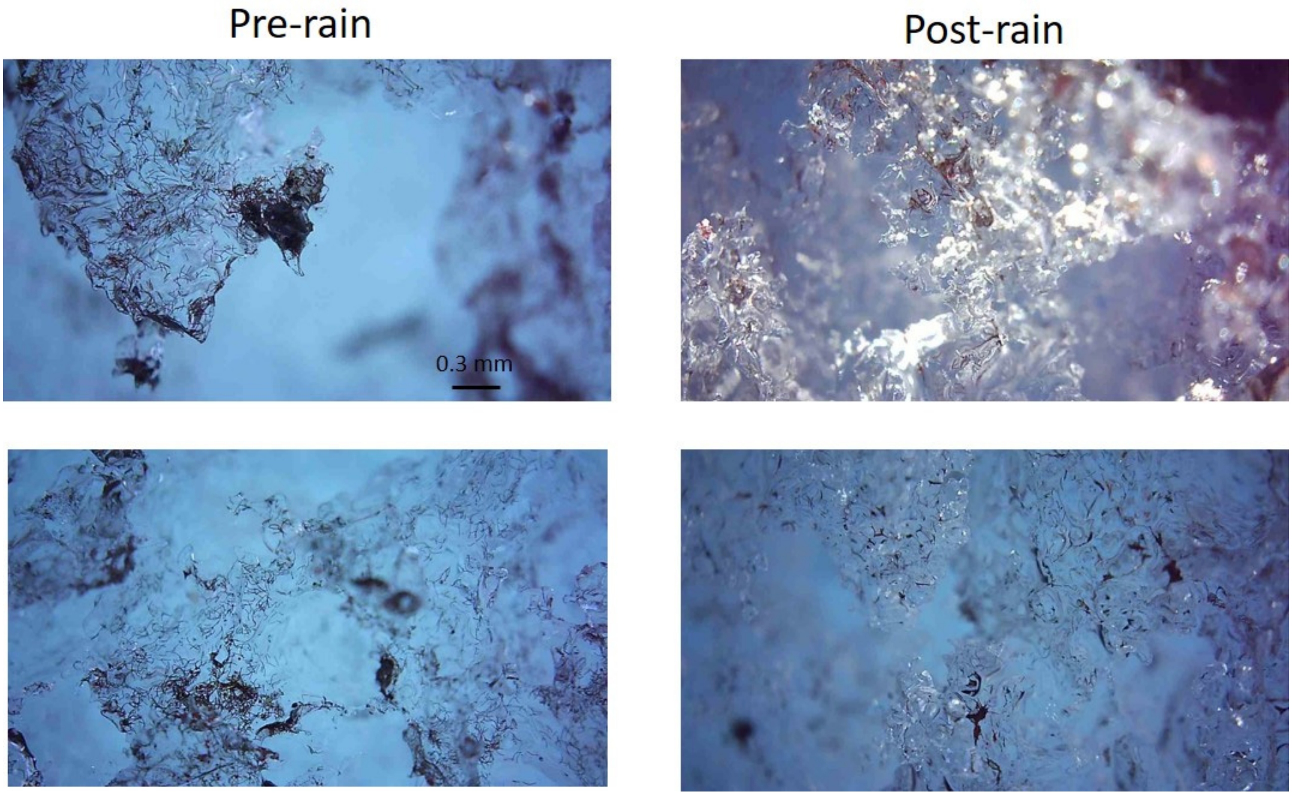

Figure 4.3. Microscopic picture of ice crystals on the surface of the ice of the Greenland ice sheet before and after rain events. The cells within the ice crystals are better distributed and well developed before rain events, while the ice looks cleaner after rain events. Photos: Alexandre Anesio.

Many of those connections between physical, chemical, and biological processes on the ice are yet to be discovered. We still lack knowledge of the glacier biome and the Greenland ice sheet full diversity, and this diversity has rarely been explored. With the imminent threat of the severe alteration or disappearance of glaciers and ice sheets, we currently risk silent losses that may make themselves known at far too late a date.

5 Snow algae – different species and different habitat, but similar impact on albedo

In addition to glacier ice algae, abundant unicellular snow algae, mainly *Chlamydomonas cf. nivalis* also referred to as *Sanguina nivaloides* (Hotaling et al., 2021) are often present in snow environments (Lutz et al., 2016). Snow algae is a complete different group of microscopic plants, compared to the glacier ice algae and they also have a very different pigmentation machinery. Nevertheless, snow algae are also subjected to high amounts of solar radiation and they use carotenoids as major photo-protective pigments (Leya et al., 2009). As the winter-spring snow becomes wet, snow algae transition from green-colored motile cells to red-colored non-motile, carotenoid rich, cysts. These carotenoids, mainly consisting of astaxanthin isomers and its fatty-acid ester derivatives, provide a deep red coloration to snow, which in turn increases absorption of solar radiation and melting of snow. In the glaciers and ice sheets, where abundant snow algae are present, the consequence could be several: 1) snow melts faster, leading to a longer season of bare ice that can be colonized by glacier ice algae generating additional melting, 2) red pigmented snow algae can themselves be retained on the bare ice, contributing to darkening of the ice and 3) nutrients retained by snow algal blooms can become available to the microbial communities on the ice, generating more microbial growth on the ice.

The impact of the presence of red-pigmented algae on snow is similar to the impact of glacier ice algae on ice. A few studies demonstrated that snow algae can contribute to up to 13% reduction in snow albedo of Arctic glaciers (Lutz et al., 2016) and 17% of the total snow melting in an Alaska glacier (Ganey et al., 2017). Similarly to glacier algae, snow algae have been mapped from satellite data using ratios of reflectance at specific wavelengths (Painter et al., 2001; Takeuchi et al., 2006). However, quantifying their albedo reducing effect at large scales still requires empirical measurements of snow algae optical properties from fresh, live samples, so that they can be incorporated into simulations of snow albedo. While significant advances have been made towards rigorous descriptions of these algae in mathematical models (Cook et al., 2017), they are currently limited by a lack of direct empirical measurements of algal optical properties.

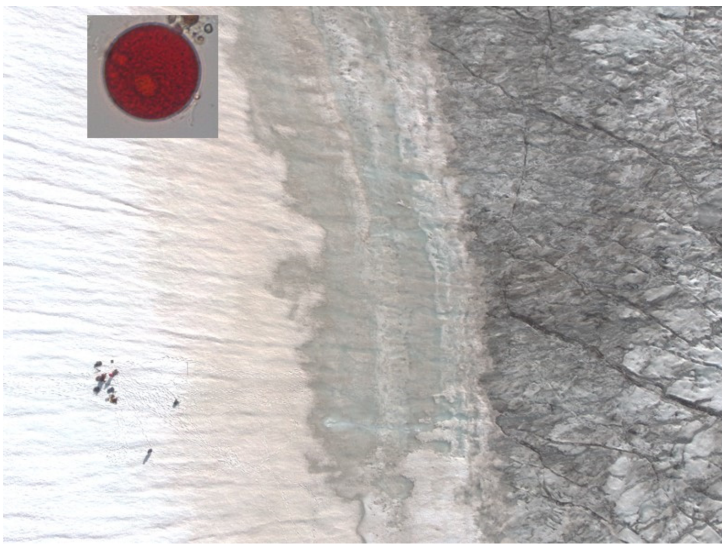

Figure 5.1. Drone image of the transition from white snow and dark ice in the Mittivakkat Glacier in the southeast Greenland with a microscopic picture of snow algae from the red snow patch. Photos: Laura Halbach.

6 Perspectives for future research

The current data available show a clear influence of the dark pigmented glacier ice algae on the melting of the Greenland ice sheet. The magnitude of this influence has still a number of uncertainties, but a recent study suggests that glacier ice algae alone could be responsible for up to 12 Gt of runoff from the western sector of the ice sheet in warm summer conditions (Cook et al., 2020). This analysis confirms the importance of the biological albedo feedback and that its omission from predictive models leads to the systematic underestimation of Greenland's future sea level contribution, especially because both the bare ice zones available for algal colonization and the length of the active growth season are set to expand in the future.

Understanding the trends in algal growth on the Greenland ice sheet is heavily constrained by the fact that there are no monitoring programs associated with the collection of biological data. Previous efforts in collecting biological data from the ice sheet are made at different times of year, different locations and with different objectives. Thus, a full picture of whether the glacial algae is growing in extension is purely based on information of the darkening measured with remote satellite imagery across time. Yet, such correlation is not yet fully proven, since other impurities (e.g., dust and black carbon) are also correlated with the darkening of the ice. Therefore, it is paramount to establish a long-term monitoring program that takes into consideration the algal growth on the GrIS and its relations with other impurities. Biological monitoring around the PROMICE (Program for Monitoring of the Greenland Ice Sheet - https://www.promice.org/) stations would allow to link weather and albedo data with algal changes. 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 also necessary first to establish methodologies and procedures for data collection. Furthermore, accurate empirical measurements of the optical properties of live glacier algae and detailed mechanistic understanding of the development of the surface ice are required to reduce the uncertainty in remotely sensed glacier algal cell concentrations.

Finally, both glacier ice and snow algae have been reported on glaciers worldwide, but fundamental understanding of the biology of these organisms are still to be determined, including their life cycle, nutrient requirements, and controls of growth to name a few. The understanding of these processes are fundamental in order to estimate the response that glacier ice and snow algae will have to global warming and their feedback with ice wastage.

7 Definitions

Albedo - is defined as the ratio between the reflected energy and the incident energy over a unit area. In the context of this report, albedo refers to ratio reflected solar energy on ice and snow and the incident solar energy. Lower albedo means darker ice and snow.

Black carbon - or soot, is part of fine particulate air pollution (PM2.5) and contributes to climate change.

Carotenoids - any of a class of mainly yellow, orange, or red fat-soluble pigments, including carotene, which give color to plants and algae parts, such tomatoes, carrots and the red coloration of snow algae.

Chytrids - are a division of zoosporic organisms in the kingdom Fungi.

ERC Deep Purple – an 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). Deep Purple puts together an international team of scientists to investigate the physical and microbial processes that darken the Greenland Ice Sheet and accelerate sea level rise.

Glacier ice algae - a group of streptophyte algae that is highly specialized to survive and thrive at the surface of glaciers and ice sheets.

Photo-protection - a biochemical process that helps organisms cope with damage caused by sunlight. In algae, such as glacier ice and snow algae, pigments such as purpurogallin and carotenoids.

Purpurogallin - is an orange-red, crystalline compound, and the aglycone of several glycosides from nutgalls and oak barks. It is also produced in great amounts in glacier ice algae. Its function in glacier ice algae seems to be associated with photo-protection.

Snow algae - a group of algae that is highly specialized to survive and thrive in snow habitats.

8 References

Anesio, A. M. and Laybourn-Parry, J.: Glaciers and ice sheets as a biome, Trends Ecol. Evol., 27(4), doi:10.1016/j.tree.2011.09.012, 2012.

Anesio, A. M., Mindl, B., Laybourn-Parry, J., Hodson, A. J. and Sattler, B.: Viral dynamics in cryoconite holes on a high Arctic glacier (Svalbard), J. Geophys. Res. Biogeosciences, 112(4), doi:10.1029/2006JG000350, 2007.

Anesio, A. M., Lutz, S., Chrismas, N. A. M. and Benning, L. G.: The microbiome of glaciers and ice sheets, npj Biofilms Microbiomes, 3(1), doi:10.1038/s41522-017-0019-0, 2017.

Anon: Avoiding dangerous climate change, Choice Rev. Online, doi:10.5860/choice.44-0979, 2006.

Bamber, J., Van Den Broeke, M., Ettema, J., Lenaerts, J. and Rignot, E.: Recent large increases in freshwater fluxes from Greenland into the North Atlantic, Geophys. Res. Lett., doi:10.1029/2012GL052552, 2012.

Bamber, J. L., Layberry, R. L. and Gogineni, S. P.: A new ice thickness and bed data set for the Greenland ice sheet: 1. Measurement, data reduction, and errors, J. Geophys. Res. Atmos., doi:10.1029/2001JD900054, 2001.

Bellas, C. M., Anesio, A. M., Telling, J., Stibal, M., Tranter, M. and Davis, S.: Viral impacts on bacterial communities in Arctic cryoconite, Environ. Res. Lett., 8(4), doi:10.1088/1748-9326/8/4/045021, 2013.

Bellas, C. M., Anesio, A. M. and Barker, G.: Analysis of virus genomes from glacial environments reveals novel virus groups with unusual host interactions, Front. Microbiol., 6(JUL), doi:10.3389/fmicb.2015.00656, 2015.

Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K. and Steffen, K.: Greenland ice sheet albedo feedback: Thermodynamics and atmospheric drivers, Cryosphere, doi:10.5194/tc-6-821-2012, 2012.

Van Den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., Van Berg, W. J. De, Van Meijgaard, E., Velicogna, I. and Wouters, B.: Partitioning recent Greenland mass loss, Science (80-.)., doi:10.1126/science.1178176, 2009.

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, doi:10.5194/tc-14-309-2020, 2020.

Fiołka, M. J., Takeuchi, N., Sofińska-Chmiel, W., Wójcik-Mieszawska, S., Irvine-Fynn, T. and Edwards, A.: Morphological and spectroscopic analysis of snow and glacier algae and their parasitic fungi on different glaciers of Svalbard, Sci. Rep., 11(1), doi:10.1038/S41598-021-01211-8, 2021.

Ganey, G. Q., Loso, M. G., Burgess, A. B. and Dial, R. J.: The role of microbes in snowmelt and radiative forcing on an Alaskan icefield, Nat. Geosci., 10(10), 754–759, doi:10.1038/NGEO3027, 2017.

He, T., Liang, S., Yu, Y., Wang, D., Gao, F. and Liu, Q.: Greenland surface albedo changes in July 1981-2012 from satellite observations, Environ. Res. Lett., doi:10.1088/1748-9326/8/4/044043, 2013.

Hodson, A. J., Mumford, P. N., Kohler, J. and Wynn, P. M.: The High Arctic glacial ecosystem: New insights from nutrient budgets, Biogeochemistry, 72(2), 233–256, doi:10.1007/S10533-004-0362-0, 2005.

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.

Hotaling, S., Lutz, S., Dial, R. J., Anesio, A. M., Benning, L. G., Fountain, A. G., Kelley, J. L., McCutcheon, J., Skiles, S. M. K., Takeuchi, N. and Hamilton, T. L.: Biological albedo reduction on ice sheets, glaciers, and snowfields, Earth-Science Rev., 220, doi:10.1016/J.EARSCIREV.2021.103728, 2021.

Keegan, K. M., Albert, M. R., McConnell, J. R. and Baker, I.: Climate change and forest fires synergistically drive widespread melt events of the Greenland Ice Sheet, Proc. Natl. Acad. Sci. U. S. A., 111(22), 7964–7967, doi:10.1073/PNAS.1405397111, 2014.

Leya, T., Rahn, A., Lütz, C. and Remias, D.: Response of arctic snow and permafrost algae to high light and nitrogen stress by changes in pigment composition and applied aspects for biotechnology, FEMS Microbiol. Ecol., 67(3), 432–443, doi:10.1111/J.1574-6941.2008.00641.X, 2009.

Ling, H. U. and Seppelt, R. D.: Snow algae of the windmill islands, continental antarctica. mesotaenium berggrenii (zygnematales, chlorophyta) the alga of grey snow, Antarct. Sci., 2(2), 143–148, doi:10.1017/S0954102090000189, 1986.

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.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T.: Global warming of 1.5°C An IPCC Special Report., 2018.

Di Mauro, B., Garzonio, R., Baccolo, G., Franzetti, A., Pittino, F., Leoni, B., Remias, D., Colombo, R. and Rossini, M.: Glacier algae foster ice-albedo feedback in the European Alps, Sci. Rep., 10(1), doi:10.1038/S41598-020-61762-0, 2020.

McCutcheon, J., Lutz, S., Williamson, C., Cook, J. M., Tedstone, A. J., Vanderstraeten, A., Wilson, S. A., Stockdale, A., Bonneville, S., Anesio, A. M., Yallop, M. L., McQuaid, J. B., Tranter, M. and Benning, L. G.: Mineral phosphorus drives glacier algal blooms on the Greenland Ice Sheet, Nat. Commun., 12(1), doi:10.1038/S41467-020-20627-W, 2021.

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., 10(MAR), doi:10.3389/fmicb.2019.00557, 2019.

Procházková, L., Řezanka, T., Nedbalová, L. and Remias, D.: Unicellular versus filamentous: The glacial alga ancylonema alaskana comb. et stat. nov. and its ecophysiological relatedness to ancylonema nordenskioeldii (zygnematophyceae, streptophyta), Microorganisms, 9(5), doi:10.3390/MICROORGANISMS9051103, 2021.

Remias, D., Schwaiger, S., Aigner, S., Leya, T., Stuppner, H. and Lütz, C.: Characterization of an UV- and VIS-absorbing, purpurogallin-derived secondary pigment new to algae and highly abundant in Mesotaenium berggrenii (Zygnematophyceae, Chlorophyta), an extremophyte living on glaciers, FEMS Microbiol. Ecol., 79(3), 638–648, doi:10.1111/J.1574-6941.2011.01245.X, 2012a.

Remias, D., Holzinger, A., Aigner, S. and Lütz, C.: Ecophysiology and ultrastructure of Ancylonema nordenskiöldii (Zygnematales, Streptophyta), causing brown ice on glaciers in Svalbard (high arctic), Polar Biol., 35(6), 899–908, doi:10.1007/S00300-011-1135-6, 2012b.

Rignot, E., Velicogna, I., Van Den Broeke, M. R., Monaghan, A. and Lenaerts, J.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophys. Res. Lett., doi:10.1029/2011GL046583, 2011.

Ryan, J. C., Hubbard, A., Stibal, M., Irvine-Fynn, T. D., Cook, J., Smith, L. C., Cameron, K. and Box, J.: Dark zone of the Greenland Ice Sheet controlled by distributed biologically-active impurities, Nat. Commun., 9(1), doi:10.1038/S41467-018-03353-2, 2018.

Sharp, M. and Tranter, M.: Glacier biogeochemistry, Geochemical Perspect., doi:10.7185/geochempersp.6.2, 2017.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., A, G., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V. R., Bjørk, A. A., Blazquez, A., Bonin, J., Colgan, W., Csatho, B., Cullather, R., Engdahl, M. E., Felikson, D., Fettweis, X., Forsberg, R., Hogg, A. E., Gallee, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B., Hanna, E., Harig, C., Helm, V., Horvath, A., Horwath, M., Khan, S., Kjeldsen, K. K., Konrad, H., Langen, P. L., Lecavalier, B., Loomis, B., Luthcke, S., McMillan, M., Melini, D., Mernild, S., Mohajerani, Y., Moore, P., Mottram, R., Mouginot, J., Moyano, G., Muir, A., Nagler, T., Nield, G., Nilsson, J., Noël, B., Otosaka, I., Pattle, M. E., Peltier, W. R., Pie, N., Rietbroek, R., Rott, H., Sandberg Sørensen, L., Sasgen, I., Save, H., Scheuchl, B., Schrama, E., Schröder, L., Seo, K. W., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T., Talpe, M., Tarasov, L., van de Berg, W. J., van der Wal, W., van Wessem, M., Vishwakarma, B. D., Wiese, D., Wilton, D., Wagner, T., Wouters, B. and Wuite, J.: Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature, 579(7798), 233–239, doi:10.1038/s41586-019-1855-2, 2020.

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.

Takeuchi, N.: Seasonal and altitudinal variations in snow algal communities on an Alaskan glacier (Gulkana glacier in the Alaska range), Environ. Res. Lett., 8(3), doi:10.1088/1748-9326/8/3/035002, 2013.

Takeuchi, N., Dial, R., Kohshima, S., Segawa, T. and Uetake, J.: Spatial distribution and abundance of red snow algae on the Harding Icefield, Alaska derived from a satellite image, Geophys. Res. Lett., 33(21), doi:10.1029/2006GL027819, 2006.

Takeuchi, N., Tanaka, S., Konno, Y., Irvine-Fynn, T. D. L., Rassner, S. M. E. and Edwards, A.: Variations in phototroph communities on the ablating bare-ice surface of glaciers on brøggerhalvøya, svalbard, Front. Earth Sci., 7, doi:10.3389/FEART.2019.00004, 2019.

Wang, S., Tedesco, M., Xu, M. and Alexander, P. M.: Mapping Ice Algal Blooms in Southwest Greenland From Space, Geophys. Res. Lett., 45(21), 11,779-11,788, doi:10.1029/2018GL080455, 2018.

Wientjes, I. G. M. and Oerlemans, J.: An explanation for the dark region in the western melt zone of the Greenland ice sheet, Cryosphere, doi:10.5194/tc-4-261-2010, 2010.

Wientjes, I. G. M., Van De Wal, R. S. W., Reichart, G. J., Sluijs, A. and Oerlemans, J.: Dust from the dark region in the western ablation zone of the Greenland ice sheet, Cryosphere, doi:10.5194/tc-5-589-2011, 2011.

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.

Williamson, C. J., Turpin-Jelfs, T., Nicholes, M. J., Yallop, M. L., Anesio, A. M. and Tranter, M.: Macro-Nutrient Stoichiometry of Glacier Algae From the Southwestern Margin of the Greenland Ice Sheet, Front. Plant Sci., 12, doi:10.3389/FPLS.2021.673614, 2021.

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.

Yoshimura, Y., Kohshima, S. and Ohtani, S.: A community of snow algae on a Himalayan glacier: Change of algal biomass and community structure with altitude, Arct. Alp. Res., 29(1), 126–137, doi:10.2307/1551843, 1997.

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