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Spheroidal carbonaceous particles in cryoconite sediment on the Russell glacier, Southwest Greenland

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Abstract In this study, we analysed the organic and inorganic content of the cryoconite holes along the altitudinal gradient at the lower elevations of the Russell glacier ablation zone in Southwest Greenland. We specifically focus on less studied industrial microscopic spheroidal carbonaceous particles (SCP; part of black carbon) to get more insights about their accumulation patterns on the glacier surface. We found no clear SCP distribution pattern, including concentration values. This outcome underlines the complexity of the ice margin zone and draws attention for further research on this topic with the inclusion of multiyear evaluation of SCP concentration at the even wider area that could possibly give results that can be compared to the emission source and long-way air pollution validation. In addition, our results indicate that during the summer of 2016, algae composition was formed of both green algae (Chlamydomonadaceae, Mesotaeniaceae) and cyanobacteria (Oscillatoriaceae). Green algae had a larger relative proportion than cyanobacteria in the cryoconite holes throughout the studied gradient.

Keywords • *Arctic* • *Greenland Ice Sheet* • *spheroidal carbonaceous particles* • *mineral matter*

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INTRODUCTION

Because of ice-albedo and temperature feedbacks, the temperature in the Arctic has increased twice as much as in comparison to the global rate (Mayewski *et al*. 2014; Sand *et al*. 2016). The Greenland Ice Sheet (GrIS) in particular has lost the considerable amount of its mass during recent decades and this process continues at an accelerating rate due to increased surface melt (Bougamont *et al*. 2014; Dumont *et al*. 2014; Aschwanden *et al*. 2016). The surface of the GrIS has greatly darkened in the last decades, thus absorbing more solar radiation and accelerating ice melting (Sand *et al*. 2016). One of such positive feedback factors is the formation of cryoconite granules and holes. Cryoconite is a combination of microorganisms, dust, microcharcoal particles and soot particles (Wharton 1985). Microorganisms such as algae, Archaea, bacteria, cyanobacteria, fungi, and Protista, are widespread in cryoconite holes (Kaczmarek *et al*. 2016), which forms one of the most common supraglacial environs on ice surfaces around the world (Hodson *et al*. 2008). Formation and settling of cryoconite granules and holes on ice sheets is of great significance as they reduce ice surface albedo (Stibal *et al*. 2012), and aid changing biogeochemical processes (Tedesco *et al*. 2016a; Anderson *et al*. 2017). For example, pigmented algae themselves on the ice surface can significantly decrease the albedo of the GrIS (Wientjes *et al*. 2011; Lutz *et al*. 2014; Musilova *et al*. 2016; Stibal *et al.* 2017).

There is an ongoing debate relating to the relative importance of the presence of inorganic particles, debris and microorganisms (bacteria and algae) on the ice sheet, both directly on the surface and within cryoconite holes in relation to their role(s) in the ice-sheet melt. Yallop *et al*. (2012) carried out photophysiological measurements on the ice sheet surface in Southwest Greenland and found that the phototrophic community growing directly on the bare ice, through their photophysiology, most likely have an important role in changing albedo, and subsequently may impact melt rates on the GrIS. Over the last decade, other studies have showed that the black carbon induced albedo change can exert a large influence on Arctic climate by advancing the timing of snow and ice melt and triggering the snow-albedo feedback, i.e. potentially more important than greenhouse gases alone (Skiles *et al.* 2018; Rupper *et al*. 2013; Hansen, Nazarenko 2004; Jacobson 2004). Just a few parts-per-billion of black carbon (soot) can reduce the albedo of snow by 1–4%, as the black carbon strongly absorbs solar radiation (AMAP 2011a, b, 2015). However, more local studies are necessary to establish the current status of the black carbon concentrations that can be used to improve the knowledge on current black carbon deposition and for improvement of regional deposition trends within the Arctic (Ruppel 2015).

Considering contribution of cryoconite on surface melting at GrIS (Stibal *et al*. 2010; Uetake *at al.* 2010; Yallop *et al*. 2012; Lutz *et al*. 2014) we assess the content of the cryoconite holes collected in August 2016, along altitudinal gradient at the lower elevations of the Russell glacier ablation zone in the Southwest Greenland. We specifically focus on less studied industrial microscopic spheroidal carbonaceous particles (SCP; part of black carbon) to get more insights about their accumulation patterns on the glacier surface. By conducting current research we reveal how the composition of cryoconite holes change and what is the concentration of SCP due to altitude and distance from the ice margin.

MATERIAL AND METHODS

Study area

Our study area is located on the Russell glacier, 25 km away from Kangerlussuaq airport (Fig. 1). The Russell glacier is an outlet glacier of the southwest part of the Greenland Ice Sheet. The proglacial streams of the Russell and the adjacent Leverett glacier feed the 1–2 km wide Sandflugtdalen proglacial valley-sandur (Storms *et al*. 2012), which is periodically flooded by jökulhlaups providing silt and sand sediments (Russell 1989, 2007, 2009; Česnulevičius *et al*. 2009; Russell *et al*. 2011). The Sandflugtdalen is a great source-area for wind-transported dust, as well as dirty ice surface and marginal moraines (Engels, Helmens 2010). The airborne silt can remain in aerial suspension for a long time and can be transported over considerable distances (Clarhäll 2011).

The mean annual air temperature at Kangerlussuaq airport was -5.0 °C and -3.9 °C for the periods 1974–2012 and 2001–2012 respectively (Mernild *et*

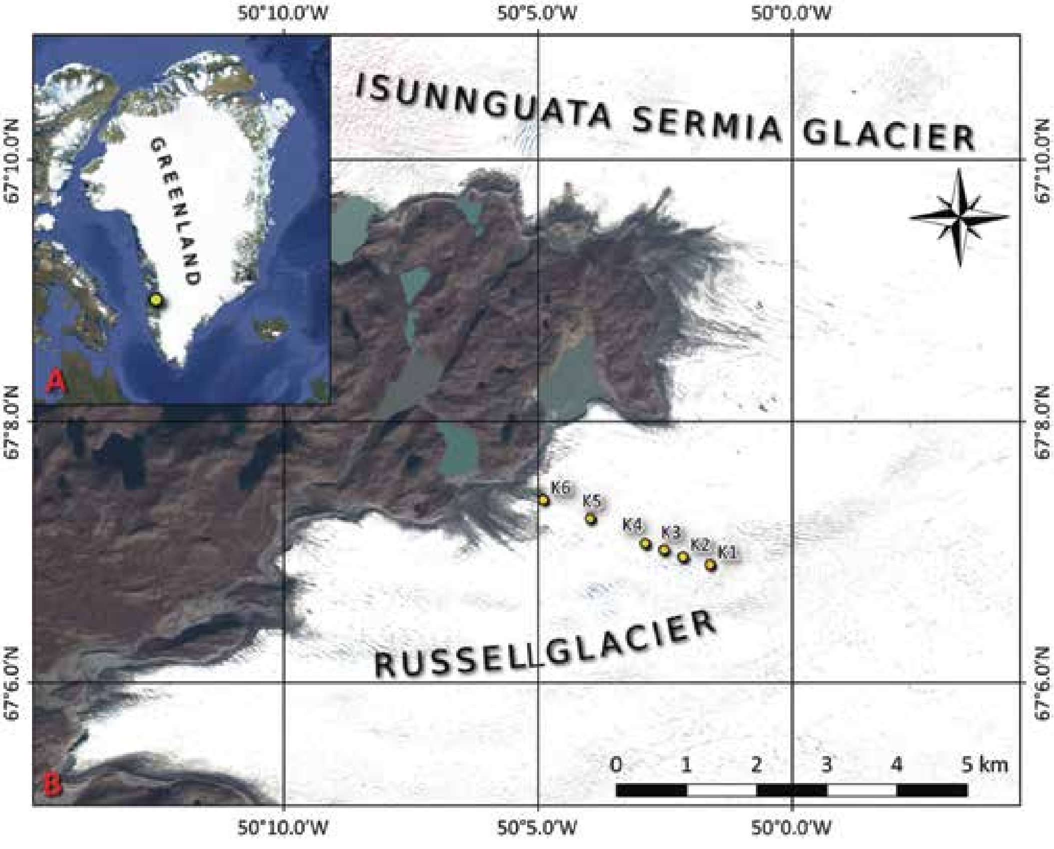

Fig. 1 Location: A – study area in Southwest Greenland, B – studied transect at the Russell glacier

al. 2014). The mean annual precipitation at Kangerlussuaq airport was 242 mm (1981–2012) with an increase to 258 mm in recent years (2001–2012) (Mernild *et al*. 2015). The mass balance of the GrIS is negative during the past 20 years, and recent warming in the western part of the GrIS has increased melt extent, surface runoff and discharge (van As *et al*. 2012).

Sampling

In order to characterize algae community and impurities in the cryoconite holes, we sampled cryoconite holes along 2.5 km transect (Fig. 1) on July 29, 2016. The weather conditions during fieldworks on the Russell glacier were sunny in the course of at least one weak at the end of July and beginning of August. During the fieldworks, the air temperature was positive and even reached 20 °C near Kangerlussuaq. Melting of at least 5 cm in a day was observed on the ice surface. No rain was experienced, as it is usual for Kangerlussuaq area. First sampling site was set 3 km from glacier margin at 552 m a.s.l. and each successive sampling site was set approximately 30 m lower. Altogether 12 samples were collected from six sampling sites. At each site, two sampling points (A and B) were chosen at the distance no more than 10 m, and deposited cryoconite was collected from five nearby cryoconite holes (Table 1).

The altitude and coordinates of each sampling point were determined by using a GPS system *Magellan Promark 3*. All measurements were performed in the UTM coordinate system, zone 22N, whereas the elevations were calculated using the EGM 2008 geoid model.

Water and sediments from each cryoconite hole were taken by an extended syringe that was carefully rinsed in the nearby supraglacial river before sampling. Samples were put into 50 ml clean polyethylene bottles (mixed from five cryoconite holes). At each sampling point, depth and diameter (hole's size) of sampled cryoconite hole was measured with a measuring tape. As five samples were pooled together in one sample, the average value was calculated for each sampling point. Cryoconite samples were stored in plastic tubes, kept cold and protected from light, and shipped to the University of Helsinki for further analysis.

Table 1 The average dimensions and elevation of five sampled cryoconite holes for each sampling point

Sample	D (cm)	Depth (cm)	H (m a.s.l.)
K1A	3–4	19.8	552
K1B	3–4	12.8	
K2A	1.5	8.8	522
K2B	2–2.5	13.2	
K3A	2.5–4	14.4	494
K3B	2.5–4	16	
K4A	3–4	8.2	465
K4B	3–6	9.6	
K5A	5–9	22.8	433
K5B	3.5–5	16.8	
K6A	4–8	8.2	423
K6B	4–8	8	

Cryoconite composition analyses

Sediment content of the cryoconite holes was analysed microscopically in the Helsinki University. A known volume (1 cm^3) of sediment was subsampled, transferred to the PVC tube and added *Lycopodium* tabl*et* allowing estimate microscopic object concentrations per sample (volume) (Stockmarr 1971). Prior to adding *Lycopodium* tablet, it was dissolved in a separate tube and rinsed three times with a distil water to achieve neutral pH. The sample was mounted in the glycerol. Transferred sample on a slide was studied under the light microscope *Zeiss Imager M2* with a magnitude of 400, 200 and 1000 μm. All the pollen, fungi, microcharcoal (10–100 μm) and black carbon particles were counted. Estimates of algae relative (percentages) composition were based on the sum of all counted algae. Other microscopic remains such as fungi spores and hyphae, pollen grains and plant tissues/cells expressed as presence. This is mainly because these were only scarce findings.

Although there are two major types of black carbon particles – soot black carbon and spheroidal carbonaceous particles (SCP), in the current study only SCP were counted. The rationale behind this was pragmatic – soot particles in comparison to SCP often can be difficult to recognize and seen by the light microscope (too small to see, from transparent to black etc.). According to Hedges *et al*. (2000) and Masiello (2004) black carbon combustion continuum model, the SCP forms only during the industrial fuel combustion at high temperatures (greater than 1000 °C). Commonly, SCP size is in range of 2 to 50 μm and therefore their drift range is intermediate from km to 1000 s of km (Ruppel *et al*. 2013). There is still a lack of understanding how many and by what pattern the SCP deposit at cryoconite holes.

Loss-on-ignition method (Heiri *et al*. 2001) was applied to estimate the cryoconite sediment relative share of mineral and organic matter (expressed as percentages). Samples were combusted at 550 °C for 4 h to determine the organic matter content of the sediment and the ignition residue was estimated as the mineral matter content of the sediment.

Statistical analysis

To characterize the general relationship between algae biomass (concentration) and environmental variables, unconstrained ordination, namely the principal components analysis (PCA) was used. Environmental variables included in PCA: microcharcoal (concentration), SCP (concentration), elevation (m a.s.l.), cryoconite holes size (cm), and cryoconite holes depth (cm), mineral matter and organic matter relative content (%). As the response data was compositional and had a gradient of 0.6 SD units long, we used a linear approach (Euclidean distance) – PCA. Data was Log transformed prior analysis. CANOCO 5.04 (ter Braak, Šmilauer 2012) was used for PCA.

RESULTS

Field measurements

Field measurements of cryoconite holes dimensions reveal that depth of sampled holes varies from 7 to 26 cm with an average of 13.2 cm. The depth seems to be unrelated merely to altitude (Fig. 2), rather local topography, particle concentration, and other factors play a significant role. Nearby cryoconite holes tend to have similar dimensions. The average hole size (diameter) is larger for holes located closer to the ice margin, probably due to the enhanced melting and washing by the small supraglacial streams. The sampled cryoconite holes were not frozen, although few holes were covered by thin ice lid (Fig. 3C).

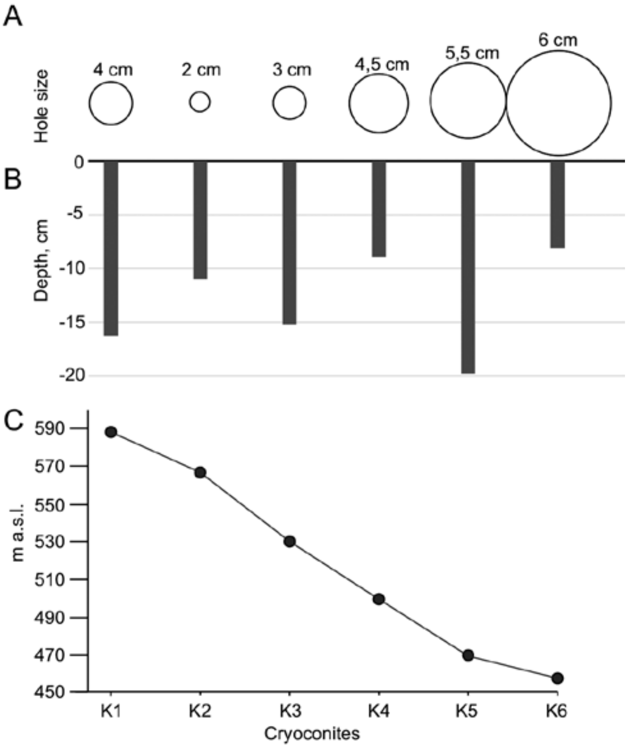

Fig. 2 Sampled cryoconite holes (A) average diameter, (B) depth (cm) and (C) altitude

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Algae composition

The overwhelming dominance of green algae (Chlamydomonadaceae, Mesotaeniaceae) was recorded in all studied cryoconite holes (Fig. 4). A higher relative abundance of Oscillatoriaceae (cyanobacteria) was observed at the lowest and highest elevations, while at middle elevations their share was minor. Within green algae, Chlamydomonadaceae had the consistent presence throughout the all cryoconite holes, with the highest abundance at 552 m a.s.l. Observed algae composition in 2016 is significantly different if compared to Uetake *et al*. (2010) observation in 2007 from the same study area when the cyanobacteria were dominating in the lower elevations of the ablation area of the Russell glacier.

Organic and inorganic matter

The highest concentration for algae was observed from 423 to 465 m a.s.l. and it stayed low beyond this elevation (Fig. 5). Chlamydomonadaceae concentration exceeded those of Oscillatoriaceae and Mesotaeniaceae. While Chlamydomonadaceae concentration decreases gradually towards higher elevation, Mesotaeniaceae have a distinct boundary at 465 m a.s.l. after which their concentration is insignificant. Oscillatoriaceae concentration varies from sample to sample with the highest concentration at the lower elevation – 423 m a.s.l. Few minor peaks of Oscillatoriaceae detected also at 465 and 552 m a.s.l.

Scarce finds of other microscopic objects of organic origin were found at several samples (Fig. 5). They most likely were brought by wind upwards the ice surface from surrounding ice-free catchment and not by a long-distance air-masses transfer. Evidence for this is, for example, pollen of *Betula nana* (dwarf birch), which is frequent in Greenland.

Overall, mineral matter content in cryoconite holes, as expected, was significantly more than organic matter (Fig. 5). Mass proportion of the mineral

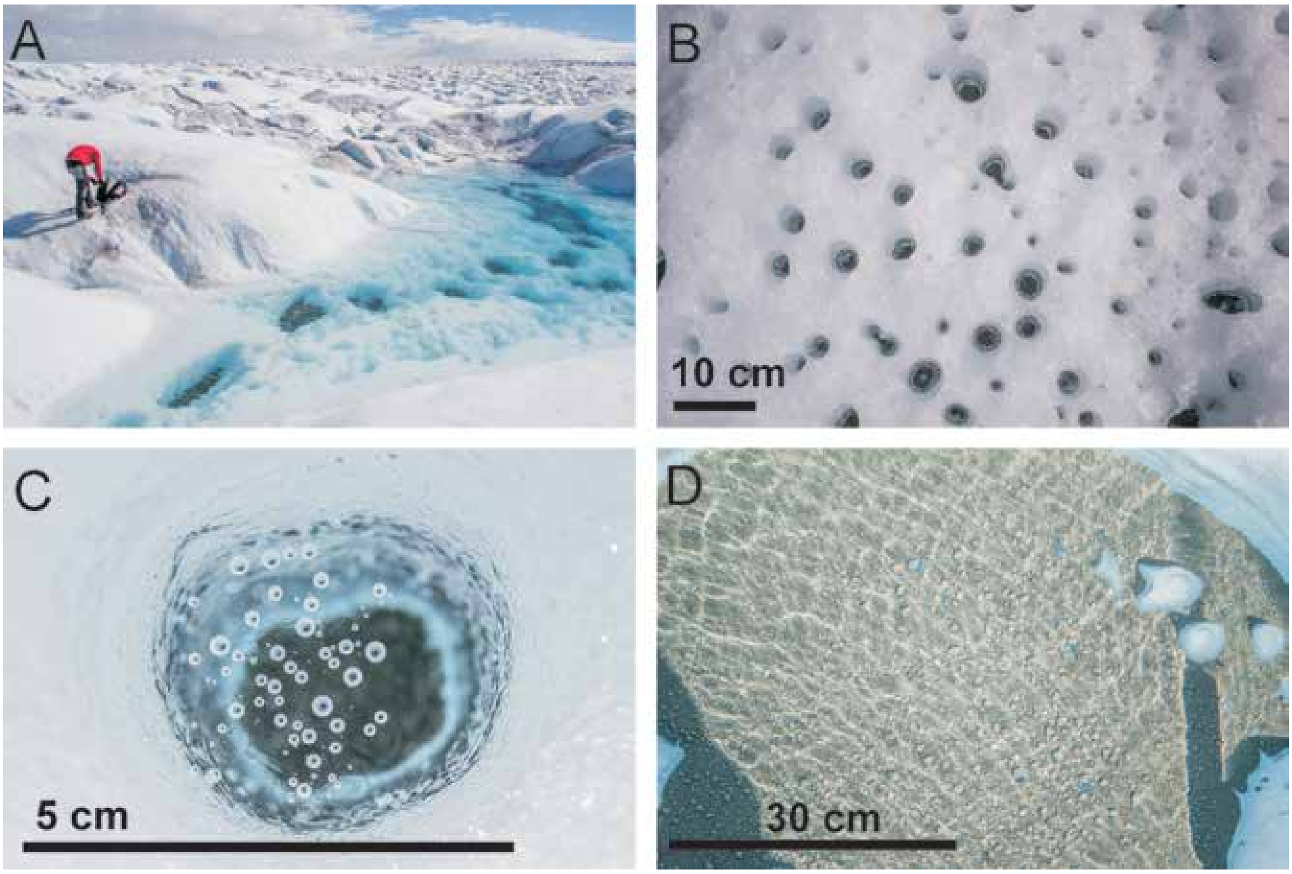

Fig. 3 A – supraglacial lake with large cryoconite holes at the bottom. B – typical cryoconite holes on the Russell glacier. C – close-up of cryoconite hole with 1-mm-thin ice lid. Notice also bubbles below ice lid due to microbial activity. D – a larger cryoconite hole with cryoconite granules at the bottom

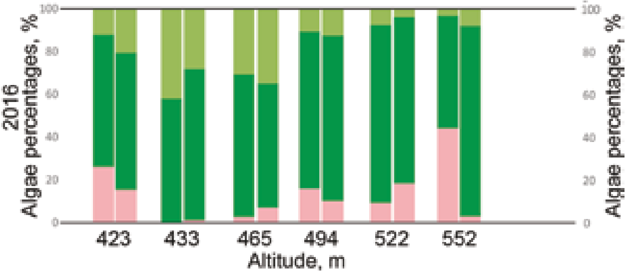

Fig. 4 Algae composition of cryoconite holes (percentages) in 2016. Light green – Mesotaeniaceae, dark green – Chlamydomonadaceae, light pink – Oscillatoriaceae

matter was between 94.2–99.3%. The highest MM content recorded at the elevation of 465 m a.s.l. and the lowest at 552 m a.s.l. Within inorganic particles, microcharcoal concentration peaked at 423, 465 and 494 m a.s.l. and SCP at 423, 465, 494 and 522 m a.s.l. (Fig. 4).

Statistical analysis

In the PCA analysis, the 1st axis explained 74% and 2nd axis explained 25% of the variance. The associations between the concentration of algae and other proxy revealed a positive relationship between Mesotaeniaceae and microcharcoal, SCP and somewhat with the mineral matter and cryoconite's hole size (diameter) (Fig. 6A). While negative association observed with an elevation and organic matter. Chlamydomonadaceae indicate a positive association with microcharcoal, SCP and negative with organic matter, elevation and hole's depth. Oscillatoriaceae have no clear associations, except a strongly negative one with the depth of cryoconite hole.

Analysed sample loading within PCA bi-plot (Fig. 6B) indicates two clusters, which most likely reflect elevation gradation, i.e. along PCA 1st axis. Hence, the concentration of algae, sediment characteristics (minerogenic and organic material) were different at lower (Cluster I) and higher (Cluster II) elevated cryoconite holes.

DISCUSSION

Our results indicate that inorganic matter concentration and proportion tend to be higher closer to the edge of ice margin. It is also true for microcharcoal and SCP aerosols, which in general are blown by the air masses from continents. Black carbon forms by incomplete combustion and occur during anthropogenic industrial combustion of biomass or fossil fu-

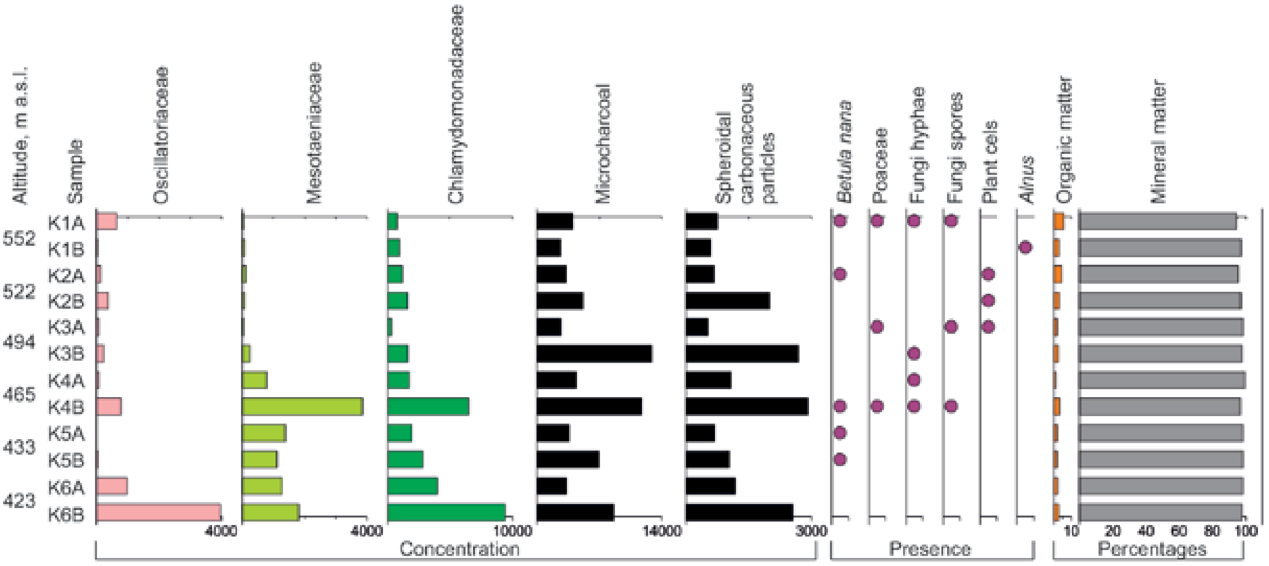

Fig. 5 Algae, microcharcoal and spheroidal carbonaceous particles concentration per sample (particles per 50 ml). Presence of other microscopic objects marked as dots. Organic and mineral matter of the cryoconite holes sediment expressed as percentages

els, in diesel and gasoline engines, or during natural forest fires (Novakov 1984; Ruppel *et al*. 2013). While other previous studies tend to analyse black carbon in general, in this study, however, we focus on SCP, which is the form of black carbon and is formed only during the industrial combustion (burning temperatures >1000°C; Ruppel *et al*. 2015). For a particular region, the concentration of SCP increased since 1850, peaking around 1910, and followed by a decline to almost pre-industrial levels after 1950. This pattern is explained by intense coal combustion in North America during the late 1800s and early 1900s, and subsequent technological advancements in combustion and changes in fuel sources (McConnell *et al*. 2007; McConnell, Edwards 2008; Keegan *et al*. 2014; Ruppel 2015). At the same time, there is a difference in the SCP pattern, because Greenland can receive both emissions from North America and Eurasia (Keegan *et al*. 2014).

The chemical composition of SCP varies considerably between and within the black carbon (Alliksaar *et al*. 1998). Black carbon is composed of >60% C with accessory elements including H, O, N and S (Goldberg 1985). Not only the concentration of SCP but also nutrient availability can increase algae biomass that in turn reduces albedo values down by 20% (Lutz *et al*. 2014; Stohl *et al*. 2006). Regarding algae biomass change, our PCA analysis indicates that green algae were positively associated with the cryoconite hole's size, microcharcoal, SCP and mineral matter (Fig. 6 (A)). Our findings suggest that inorganic material in cryoconite holes probably could enhance green algae biomass. Unfortunately, we did not test the chemical composition of SCP, microcharcoal or mineral matter to provide the evidence for such

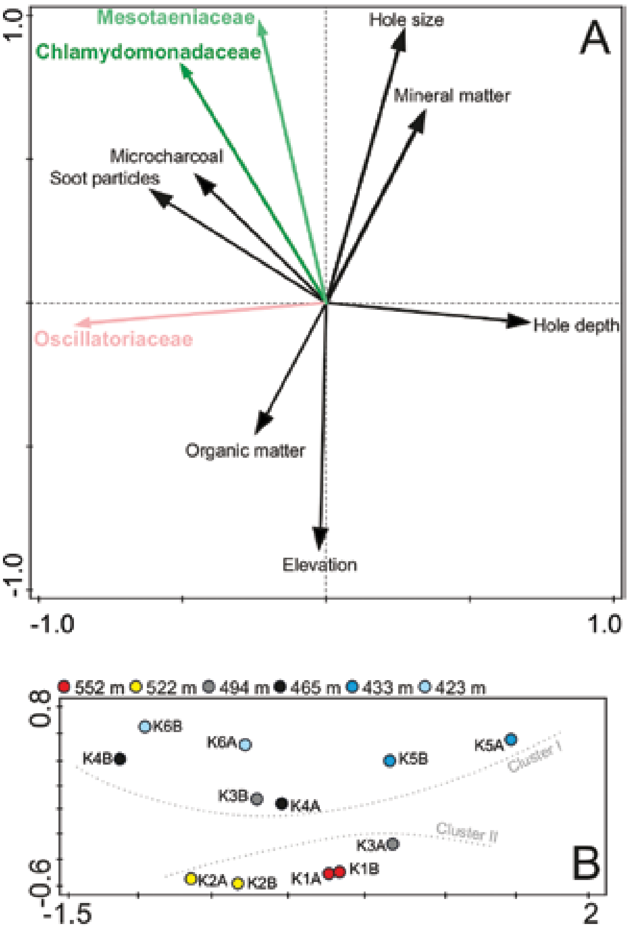

Fig. 6 Results of Principal Component Analysis showing (A) the associations between the algae and environmental variables and (B) associations only between cryoconite holes – samples

statement, but it is known that mineral matter from surrounding catchment (both brought by the wind and meltwater) can be a significant nutrient source (Telling *et al*. 2011).

Variation in SCP and mineral matter concentration at different elevations probably can be explained by the complex nature of biocryomorphology (Cook *et al*. 2015). Wientjes *et al*. (2011) found that inorganic mineral material or dust in the GrIS is of local origin, i.e., from the outcropping dust in the ice-free area next to the ice margin. Similar findings were brought by the Kalińska-Nartiša *et al*. (2017) who showed that fine-grained quartz particles in cryoconite holes on the Russell glacier are mostly of local origin, although few originate from distant sources, where dry and warm climate prevail. As the climate warms, the transport of dust from snow-free areas in the Arctic that are experiencing earlier melting of seasonal snow is a contributing source of cryoconite (Stibal *et al*. 2012; Dumont *et al*. 2014). Under ongoing climate warming, larger areas will become ice-free due to ice margin retreat and increased dust concentration will settle on GrIS surface enhancing melting rates (Tedesco *et al*. 2016a, b). Variable aeolian activity and increasing melting rates towards the glacial margin can lead to a faster emergence of sediment on the glacial surface and hence leads to albedo variations in the present ablation zone of the ice sheet (Wientjes *et al*. 2012). GrIS surface can thus concentrate SCP and mineral particles, which during ice melting can move also downwards from higher elevations (Stibal *et al*. 2012). Higher SCP concentration at the margin and higher elevation show, that there is no clear trend and more research further should be done, e.g. multiple year observations.

Regarding the organic composition of the cryoconite holes on the Russell glacier in August 2016, our results indicate that both green algae (Chlamydomonadaceae, Mesotaeniaceae) and cyanobacteria (Oscillatoriaceae) were present. In addition, the green algae had a larger relative proportion than cyanobacteria throughout the studied gradient from 423 to 552 m a.s.l. Previous research by Uetake *et al*. (2010) from the same area revealed that cyanobacteria were dominating during 2007. The magnitude of the algal bloom, as well as its development in time, has a strong interseasonal variability according to multiple observations of different groups on the ice sheet. Therefore, drawing a general conclusion about the change of the proportion of glacial algae in cryoconite from a comparison with the Uetake *et al*. (2010) study is not possible given that both studies lack temporal replicates. Furthermore, the methods used by Uetake *et al*. (2010) were not the same, because Uetake *et al*. (2010) marked out quadrats and sampled everything within the quadrats including the material directly on the surface and the cryoconite contained within holes. In the current study, solely sediment of cryoconite holes was sampled and analysed. Different organisms (or different relative abundance) might grow on the ice surface compared to those in cryoconite hole, flowing meltwaters frequently in wash green algae from the surrounding surface into the cryoconite holes in the melt season close, particularly close to the ice margin, and could reflect algae community around the cryoconite holes. Filamentous cyanobacteria are typically associated with cryoconite granules, whereas green algae dominate the bare ice surface (Stibal *et al*. 2012; Yallop *et al*. 2012). Therefore, both techniques used in the current study and in Uetake *et al*. (2010) could give different results even if they were applied in the same situation in the field. The abundance of glacial algal cells in cryoconite can be correlated with the abundance of the algae in the surrounding bare ice. However, other factors as the intensity of melt and the passive mobilization of cells can also significantly contribute to the variability in abundance of algal cells in cryoconite.

Change in the ice or snow algae composition can be attributed to variety of factors such as air temperature, altitude, distance from the ice margin, nutrient availability and source material (Mueller, Pollard 2004; Stibal *et al*. 2010; Yallop *et al*. 2012; Lutz *et al*. 2014; Cvetkovska *et al*. 2017; Anderson *et al*. 2017). Although we have not tested the air temperature connection, overall air temperature increase most probably could be a forcing base in subsequent algae and environmental change (Tingley, Huybers 2013; Lutz *et al*. 2014), and increase in GrIS melting (Tedesco *et al*. 2016b). Increased air temperature can affect also the length of the growing season, which in turn supports specific algae dominance and increased photosynthesis in cryoconite holes (Lutz *et al*. 2014). In the last ten years, the surface mass loss of the GrIS has increased, and the highest surface mass loss since 1979 has estimated for the years of 2010, 2012 and 2016 possibly affecting algal communities on the ice as well. Importantly to underline that the change of algae community from one algae dominance to other can increase or decrease surface albedo due to algae pigment change (e.g. Lutz *et al*. 2016).

Our results indicate that the algae biomass decreases with an altitude and the biomass of cyanobacteria increases with shallower cryoconite holes (Fig. 6(A)). Although there is a link between algae concentration and increased microcharcoal, SCP, and mineral matter, algae concentration decreases beyond 465 m a.s.l. Our finding is in a line with Stibal *et al*. (2010) who recognized that the variation in debris distribution on the ice surface increases microbial activity and organic matter content. Elevation gradient seems to influence cryoconite holes sediment composition and algae concentration.

Cryoconite holes on glacier surfaces are known as the hot spots of microbial diversity, which includes also a fungal community (Edwards *et al*. 2012; Singh, Singh 2012). Our observations show the presence of fungal remains such as fungal hyphae (the main mode of vegetative growth) and few unidentified fungal spores. Based on light microscopy it was not possible to distinguish whether these were of in situ or windblown objects. Dwarf birch (*Betula nana*), alder (*Alnus*) and grass (*Poaceae*) pollen grains suggest rather a local origin of these scarce findings, as they are common in present landscape of Greenland. Even though fungi spores usually tend to be of strictly local origin, it is more likely that these all particles and objects were brought to the cryoconite holes by the wind from the ice-free grounds next to the Russell glacier similarly (Stibal *et al*. 2012; Anderson *et al*. 2017).

CONCLUSIONS

In this study, we analysed the content of the cryoconite along altitudinal gradient at the lower elevations (423–552 m a.s.l.) of the Russell glacier ablation zone in Southwest Greenland. Our results indicate that green algae are the dominant group of algae in the cryoconite holes at the lower altitudes in summer 2016. Inorganic matter concentration and proportion tend to be higher closer to the edge of ice margin, supporting the idea that it mainly derives from the ice-free area next to the ice margin. However, there was no clear SCP distribution pattern, including concentration values. This outcome underlines the complexity of the ice margin zone and draws attention for further research on this topic with the inclusion of multiyear evaluation of SCP concentration at the even wider area that could possibly give results that can be compared to the emission source and long-way air pollution validation.

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REFERENCES

Alliksaar, T., Hörstedt, P., Renberg, I. 1998. Characteristic fly-ash particles from oil-shale combustion found in lake sediments. *Water Air & Soil Pollution 104*, 149–160.

AMAP, 2011a. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. *Arctic Monitoring and Assessment Programme (AMAP)*. Oslo, Norway, xii + 538 pp.

AMAP. 2011b. The Impact of Black Carbon on Arctic Climate. In: Quinn, P.K., Stohl, A., Arneth, A., Berntsen, T., Burkhart, J. F., Christensen, J., Flanner, M., Kupiainen, K., Lihavainen, H., Shepherd, M., Shevchenko, V., Skov, H., Vestreng, V. *AMAP Technical Report No. 4 (2011). Arctic Monitoring and Assessment Programme (AMAP)*. Oslo, Norway, 72 pp.

AMAP. 2015. Black carbon and ozone as Arctic climate forcers. *Arctic Monitoring and Assessment Programme (AMAP)*, Oslo, Norway, vii + 116 pp.

Anderson, N.J., Saros, J.E., Bullard, J.E., Cahoon, S.M.P., McGowan, S., Bagshaw, E.A., Barry, C.D., Bindler, R., Burpee, B.T., Carrivick, J.L., Fowler, R.A., Fox, A.D., Fritz, S.C., Giles, M.E., Hamerlik, L., Ingeman-Nielsen, T., Law, A.C., Mernild, S.H., Northington, R.M., Osburn, C.L., Pla-Rabes, S., Post, E., Telling, J., Stroud, D.A., Whiteford, E.J., Yallop, M.L., Yde, J.C. 2017. The Arctic in the twenty-first century: changing biogeochemical linkages across a paraglacial landscape of Greenland. *BioScience 67*, 118–133.

Aschwanden, A., Fahnestock, M.A., Truffer, M. 2016. Complex Greenland outlet glacier flow captured. *Nature Communications 7*, 10524, doi: http://dx.doi.org/10.1038/ncomms10524

Bougamont, M., Christoffersen, P., Hubbard, A.L., Fitzpatrick, A.A., Doyle, S.H., Carter, S.P. 2014. Sensitive response of the Greenland Ice Sheet to surface melt drainage over a soft bed. *Nature Communications 5*, 5052, doi: http://dx.doi.org/10.1038/ncomms6052

Česnulevičius, A., Šeirienė, V., Kazakauskas, V., Baltrūnas, V., Šinkūnas, P., Karmaza, B. 2009. Morphology and sediments of ice-dammed lake after its outburst, West Greenland. *Geologija 51*, 42–52.

Clarhäll, A. 2011. SKB Studies of the periglacial environment. *Report from field studies in Kangerlussuaq, Greenland 2008 and 2010, P-11-05*. Svensk Kärnbränslehantering AB, Stockholm, 49 pp.

Cook, J., Edwards, A., Hubbard, A. 2015. Biocryomorphology: Integrating microbial processes with ice surface hydrology, topography, and roughness. *Frontiers of Earth Science 3*, 1–6.

Cvetkovska, M., Huner, N.P. A., Smith, D.R. 2017. Chilling out: the evolution and diversification of psychrophilic algae with a focus on Chlamydomonadales. *Polar Biology 40*, 1169–1184.

Dumont, M., Brun, E., Picard, G., Michou, M., Libois, Q., Petit, J.-R., Geyer, M., Morin, S., Josse, B. 2014. Contribution of light-absorbing impurities in snow to

Greenland's darkening since 2009. *Nature Geoscience 7 (7)*, 509–512.

Edwards, A., Douglas, B., Anesio, A.M., Rassner, S.M., Irvine-Fynn, T.D.L., Sattler, B., Griffith, G.W. 2012. A distinctive fungal community inhabiting cryoconite holes on glaciers in Svalbard. *Fungal Ecology 6*, 168–176.

Engels, S., Helmens, K.F. 2010. *Holocene environmental changes and climate development in Greenland*. R-10-65. Svensk Kärnbränslehantering AB, Stockholm, 40 pp.

Goldberg, E.D. 1985. *Black carbon in the environment*. John Wiley & Sons, New York, 198 pp.

Hansen, J., Nazarenko, L. 2004. Soot climate forcing via snow and ice albedos. *Proceedings of the National Academy of Sciences of the United States of America 101*, 423–428.

Heiri, O., Lotter, A. F., Lemcke, G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology 25*, 101–110.

Hodson, A., Anesio, A.M., Tranter, M., Fountain, A., Osborn, M., Priscu, J., Laybourn-Parry, J., Sattler, B., 2008. Glacial Ecosystems. *Ecological Monographs 78 (1)*, 41–67.

Jacobson, M.Z. 2004. Climate response of fossil fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity. *Journal of Geophysical Research 109*, D21201.

Kaczmarek, Ł., Jakubowska, N., Celewicz-Gołdyn, S., Zawierucha, K. 2016. The microorganisms of cryoconite holes (algae, Archaea, bacteria, cyanobacteria, fungi, and Protista): a review. *Polar Record 52 (2)*, 176–203.

Kalińska-Nartiša, E., Lamsters, K., Karušs, J., Krievāns, M., Rečs, A., Meija, R. 2017. Fine-grained quartz from cryoconite holes of the Russell Glacier, southwest Greenland – a scanning electron microscopy study. *Baltica 30 (2)*, 63–73.

Lutz, S., Anesio, A.M., Villar, S.E.J., Benning, L.G. 2014. Variations of algal communities cause darkening of a Greenland glacier. *FEMS Microbiology Ecology 89 (2)*, 402–414.

Lutz, S., Anesio, A.M., Raiswell, R., Edwards, A., Newton, R.J., Gill, F., Benning, L.G. 2016. The biogeography of red snow microbiomes and their role in melting arctic glaciers. *Nature Communications 7*, 11968, doi: http://dx.doi.org/10.1038/ncomms11968

Mayewski, P.A., Sneed, S.B., Birkel, S.D., Kurbatov, A.V., Maasch, K.A. 2014. Holocene warming marked by abrupt onset of longer summers and reduced storm frequency around Greenland. *Journal of Quaternary Science 29*, 99–104.

Mernild, S.H., Hanna, E., McConnell, J.R., Sigl, M., Beckerman, A.P., Yde, J.C., Cappelen, J., Malmros, J.K., Steffen, K. 2015. Greenland precipitation trends in a long-term instrumental climate context (1890–2012): Evaluation of coastal and ice core records. *The International Journal of Climatology 35,* 303–320.

Mernild, S.H., Hanna, E., Yde, J.C., Cappelen, J., Malmros, J.K. 2014. Costal Greenland air temperature extremes and trends 1890–2010: Annual and monthly analysis. *The International Journal of Climatology 34*, 1472–1487.

Mueller, D.R., and Pollard, W.H. 2004. Gradient analysis of cryoconite ecosystems from two polar glaciers. *Polar Biology 27*, 66–74.

Musilova, M., Tranter, M., Bamber, J.L., Takeuchi, N., Anesio, A.M. 2016. Experimental evidence that microbial activity lowers the albedo of glaciers. *Geochemical Perspectives Letters 2*, 106–116.

Novakov, T. 1984. The role of soot and primary oxidants in atmospheric chemistry. *Science of the Total Environment 36*, 1–10.

Ruppel, M.M., Gustafsson, Ö., Rose, N.L., Pesonen, A., Yang, H., Weckström, J., Palonen, V., Oinonen, M.J., Korhola, A. 2015. Spatial and Temporal Patterns in Black Carbon Deposition to Dated Fennoscandian Arctic Lake Sediments from 1830 to 2010. *Environmental Science & Technology 49 (24)*, 13954–13963.

Ruppel, M., Lund, M.T., Grythe, H., Rose, N.L., Weckström, J., Korhola, A. 2013. Comparison of spheroidal carbonaceous particle data with modelled atmospheric black carbon concentration and deposition and air mass sources in Northern Europe. *Advanced Meteorology 393926*, 1850–2010, doi: http://dx.doi.org/10.1155/2013/393926

Ruppel, M.M. 2015. *Black carbon deposition in the European Arctic from the preindustiral to the present*. PhD Thesis, Academic dissertation. University of Helsinki, ISBN 978-951-51-1204-0.

Russell, A.J. 1989. A comparison of two recent jokulhlaups from an-ice-dammed lake, Sondre Stromfjord, West Greenland. *Journal of Glaciology 35*, 157–162.

Russell, A.J. 2007. Controls on the sedimentology of an ice-contact jökulhlaup dominated delta, Kangerlussuaq, West Greenland. *Sedimentary Geology 193*, 131–148.

Russell, A.J. 2009. Jökulhlaup (ice-dammed lake outburst flood) impact within a valley-confined sandur subject to backwater conditions, Kangerlussuaq, West Greenland. *Sedimentary Geology 215*, 33–49.

Russell, A.J., Carrivick, J.L., Ingeman-Nielsen, T., Yde, J.C., Williams, M. 2011. A new cycle of jökulhlaups at Russell Glacier, Kangerlussuaq, West Greenland. *Journal of Glaciology 57 (202)*, 238–246.

Sand, M., Berntsen, T.K., von Salzen, K., Flanner, M.G., Langner, J., Victor, D.G. 2016. Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change 6*, 286–290.

Singh, P., Singh, S.M. 2012. Characterization of yeast and filamentous fungi isolated from cryoconite holes of Svalbard, Arctic. *Polar Biology 35*, 575–583.

Skiles, S.M., Flanner, M., Cook, J.M., Dumont, M., Painter, T.H. 2018. Radiative forcing by light-absorbing particles in snow. *Nature Climate Change 8*, 964–971.

Stibal, M., Lawson, E.C., Lis, G.P., Mak, K.M., Wadham, J.L., Anesio, A.M. 2010. Organic matter content and quality in supraglacial debris across the ablation zone of the Greenland ice sheet. *Annals of Glaciology 51*, 1–8.

Stibal, M., Šabacka, M., Žárský, J. 2012. Biological processes on glacier and ice sheet surfaces. *Nature Geoscience 5*, 771–774.

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., Calì Quaglia, F., Remias, D. 2017. Algae drive enhanced darkening of bare ice on the Greenland ice sheet. *Geophysical Research Letters 44 (22),* 11463–11471.

Stockmarr, J. 1971. Tablets with spores used in absolute pollen analysis. *Pollen Spores 13*, 615–621.

Stohl, A., Andrews, E., Burkhart, J. F., Forster, C., Herber, A., Hoch, S.W., Kowal, D., Lunder, C., Mefford, T., Ogren, J.A., Sharma, S., Spichtinger, N., Stebel, K., Stone, R., Ström, J., Tørseth, K., Wehrli, C., Yttri, K.E. 2006. Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004. *Journal of Geophysical Research. Atmospheres 111*: D22214, doi: http://dx.doi.org/10.1029/2006JD007216

Storms, J.E., de Winter, I.L., Overeem, I., Drijkoningen, G.G., Lykke-Andersen, H. 2012. The Holocene sedimentary history of the Kangerlussuaq Fjord-valley fill, West Greenland. *Quaternary Science Reviews 35*, 29–50.

Tedesco, M., Doherty, S., Fettweis, X., Alexander, P., Jeyaratnam, J., Stroeve, J. 2016a. The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100). *Cryosphere 10*, 477–496.

Tedesco, M., Mote, T., Fettweis, X., Hanna, E., Jeyaratnam, J., Booth, J.F., Datta, R., Briggs, K. 2016b. Arctic cut-off high drives the poleward shift of a new Greenland melting record. *Nature Communications 11723*, doi: http://dx.doi.org/10.1038/ncomms11723

Telling, J., Anesio, A.M., Tranter, M., Irvine-Fynn, T., Hodson, A., Butler, C., Wadham, J. 2011. Nitrogen fixation on Arctic glaciers, Svalbard. *Journal of Geophysical Research. Biogeosciences 116*, G03039, doi: http://dx.doi.org/10.1029/2010JG001632

Ter Braak, C.J.F., Šmilauer, P. 2012. Canoco Reference Manual and User's Guide: Software for Ordination (Version 5.0). *Microcomputer Power.* Ithaca, New York, 496 pp.

Tingley, M., Huybers, P. 2013. Recent temperature extremes at high northern latitudes unprecedented in the past 600 years. *Nature 496*, 201–205.

Uetake, J., Naganuma, T., Hebsgaard, M.B., Kanda, H., Kohshima, S. 2010. Communities of algae and cyanobacteria on glaciers in west Greenland. *Polar Science 4 (1)*, 71–80.

Van As, D.V., Hubbard, A.L., Hasholt, B., Mikkelsen, A.B., Van den Broeke, M.R., Fausto, R.S. 2012. Large surface meltwater discharge from the Kangerlussuaq sector of the Greenland ice sheet during the record-warm year 2010 explained by detailed energy balance observations. *Cryosphere 6 (1)*, 199–209.

Wharton, R.A., McKay, C.P., Simmons, G.M., Parker, B.C. 1985. Cryoconite holes on glaciers. *Bioscience 35*, 499–503.

Wientjes, I.G.M., Van de Wal, R.S. W., Reichart, G.J., Sluijs, A., Oerlemans, J. 2011. Dust from the dark region in the western ablation zone of the Greenland ice sheet. *Cryosphere 5*, 589–601.

Wientjes, I.G.M., Van De Wal, R.S.W., Schwikowski, M., Zapf, A., Fahrni, S., Wacker, L. 2012. Carbonaceous particles reveal that Late Holocene dust causes the dark region in the western ablation zone of the Greenland ice sheet. *Journal of Glaciology 58*, 787–794.

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., Roberts, N.W. 2012. Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland ice sheet. *The ISME Journal 6*, 2302–2313.