Biotope and biocenosis of cryoconite hole ecosystems on Ecology Glacierin the maritime Antarctic

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Abstract: Despite recent great interest in glacier ecosystems in the continental Antarctic, little is known about their maritime counterparts. Our study presents descriptive data on cryoconite sediments and cryoconite holes on Ecology Glacier (King George Island) to accomplish three main objectives: (a) to identify main eukaryotic (algae, invertebrates) and prokaryotic (cyanobacteria) components of microbial communities; (b) to provide a “baseline” of community composition, organic matter and artificial contamination; and (c) identify key abiotic factors that might be important in community assembly. Cryoconite holes were sampled along an altitudinal gradient of

Ecology Glacier in January, mid Austral Summer 2017. Cryoconite holes located in lower altitude were deeper than those located in the middle and the highest altitude. Seventeen species of algae and cyanobacteria with biomass of 0.79 to 5.37 μg/cm^3 have been found in sediments. Dominant species were cyanobacterial *Pseudanabaena frigida* and Bacillariophyceae *Microcostaus* sp. Biomass of Bacillariophyceae was significantly higher than that of Chlorophyta and Cyanobacteria. We found three species of rotifers (two potentially new to science) and for the first time a glacier dwelling Acari (suspension feeder, *Nanorchestes nivalis*). Organic matter content ranged from 5.4% to 7.6%. Investigated artificial radionuclides included ^{137}Cs, ^{238}Pu, $^{239+240}$Pu and ^{241}Am. ^{210}Pb seems to be related to organic matter content. Overall, cryoconite holes on Ecology Glacier present unique habitats that serve as biodiversity hotspots of psychrophiles, source of organic matter, matrices for radioactivity tracking and model for observing changes in supraglacial ecosystems in Maritime Antarctic.

Keywords: algae, Antarctic cryoconite, biodiversity, contamination of polar regions, Acari and Freshwater Rotifera, glacial ecosystems, microbial communities

1. Introduction

For years glaciers have been considered as unproductive and mostly lifeless systems. Over the last two decades, a new view of glaciers as the coldest of Earth's biomes and biodiversity hotspots of psychrophiles has emerged (Anesio & Laybourn-Parry 2012, Stibal et al. 2020). Glaciers' biological activity peaks during summers (Hodson et al. 2008, Anesio & Laybourn-

Parry 2012) when liquid water accumulates on the surface of glaciers (supraglacial zone) providing habitable space for microbial communities. Most of the organisms within those communities are unique and highly adapted to cope with extreme cold, frequent cycles of melting and freezing, flushing of nutrients, and high UV radiation (e.g., Hodson et al. 2008, Zawierucha et al. 2019, Samui et al. 2018). Through their activity, they can affect local carbon and iron budgets, and rates of ice melting (Anesio et al. 2009, Tedstone et al. 2017, Williamson et al. 2018).

The most biologically diverse, active, and productive glacial communities are those associated with cryoconite holes (Takeuchi et al. 2010, Stibal et al. 2015, 2020, Cook et al. 2015, Zawierucha et al. 2015). They form when supraglacial sediment (mineral debris deposited on the surface of ice by wind, water, and rockfall) along with microorganisms (e.g., bacteria, algae, and invertebrates) (Takeuchi et al. 2001a, Hodson et al. 2008, Cook et al. 2015) absorb more solar radiation than the surrounding ice and melt into the ice. Cryoconite holes are considered biodiversity hotspots, bioreactors producing organic matter, and potential sinks of heavy metals and other contaminants (Wharton et al. 1985, Stibal et al. 2010, Baccolo et al. 2017, Łokas et al. 2016, 2018, 2019, Zawierucha et al. 2018). Many species are associated exclusively with these unique glacial ecosystems (Dastych et al. 2003, Edwards et al. 2013, Zwierucha et al. 2015, 2016a). Although the seedbank of cryoconite communities originates from habitats surrounding glaciers (e.g., soils, supraglacial gravel and streams) (Franzetti et al. 2017), they develop their own distinct signatures (Franzetti et al. 2017, Stibal et al. 2020, Zawierucha et al. 2016a). Even though studies on biological and ecological characteristics of glaciers have been conducted worldwide (Franzetti et al. 2017, Segawa et al. 2017, Stibal et al. 2015, Zawierucha et al. 2019) including Antarctica, the knowledge on glaciers in the Maritime Antarctica remains scarce. Despite the fact that Antarctica is the most extensive ice covered part of the world, its glacier ecosystems seem to be poorly known, with comprehensive studies conducted only on few glaciers (Porazinska et al. 2004; Sommers et al. 2019; Stanish et al, 2013).

Antarctica is the only continent covered by 97% ice, and thus it constitutes the largest freshwater reservoir on Earth. Glaciers play an important role in Antarctic ecosystems as a source of water and nutrients for forefields in polar deserts (Bagshaw et al. 2013) but also as a source of nutrients for aquatic systems (Hodson et al. 2017). Despite a long history of studies on glacial ecosystems in the Continental Antarctic, special attention has been given only to microbial diversity and its function, cryoconite holes morphology and biochemistry mostly on McMurdo Dry Valley glaciers (Bagshaw et al. 2007, 2011, 2013, Fountain et al. 2004, Mueller et al. 2001, Porazinska et al. 2004, Sommers et al. 2019, Wharton et al. 1985), the knowledge on glacial ecosystems in the Maritime Antarctica remain scarce. Maritime Antarctica, especially the Antarctic Peninsula, is a transition zone, where climatic conditions vary between a temperate north and more polar-influenced south. Therefore, specifically the Antarctic Peninsula is characterized by unique conditions including climate and isolation from human impact. Owing to its remote location, the Antarctic Peninsula has been suggested as an area suitable for monitoring the effects of climate change (Braun & Gossman 2002) and air pollution (Artaxo et al. 1992). Given that cryosphere is one of the fastest changing biomes (Quayle et al. 2002, Robinson et al. 2003, Convey 2013), physical and biological description of supraglacial habitats for developing a better understanding of glacial ecosystem functioning, their biodiversity, human impact and organic matter losses from ice to downstream ecosystems is urgent..

The present study lays out groundwork on cryoconite hole ecosystems of Ecology Glacier in Maritime Antarctic. Specifically, it identifies diversity and composition of microbial eukaryotes (algae, invertebrates) and prokaryotes, characterizes abiotic conditions, and describes the extent of biotic/abiotic interactions.

2. Material and methods

2.1 Study area

2.1.1. King George Island

King George Island (KGI) is located between 61°54'-62°16'S and 57°35'-59°02'W in the South Shetland archipelago (West Antarctica, Figure 1). This island was formed on a crustal block with a thickness of 30-32 km separated from the Antarctic Peninsula (Birkenmajer et al. 1991). The KGI rocks (Igneous rock) are mainly rich in both calcium and alkali metals and there is a low abundance of trace elements. More than 90% of the land is covered by ice with the highest point being 650 m a.s.l. with the glacier equilibrium-line at about 100 m a.s.l (Bintanja 1995). The whole island is characterised by a typical maritime climate with low annual amplitudes of air temperature (2°C), high humidity (82%) (Martianov & Rakusa-Suszczewski 1989) as well as constant cloud cover (Rakusa-Suszczewski et al. 1993, Knap et al. 1996, Braun et al. 2001, Ferron et al. 2004). The average annual (1977-1998) sum of precipitation at the Arctowski station is 499.8 mm with two maxima in March and September (58.3 mm and 47.4 mm respectively), and two minima in August and December (28.2 mm and 34.7 mm respectively) (Marsz et al. 2000).

2.1.2. Ecology Glacier

Ecology Glacier (62°11′S, 58°28′W) is located in the southern part of the KGI. The glacier is an outlet from the Warszawa Icefield flowing north-east. The central part of the front empties into the Suszczewski Cove of the Admiralty Bay while lateral parts of the lobe terminate on land forming marginal moraines. The surface area of the basin of Ecology Glacier is 5.21 km^2 (Pętlicki et al. 2017). Overall glacier mass balance is driven by both frontal and surface ablation, which over the last 40 years has been negative (Pętlicki et al. 2017). This reflects a concurrent climate warming trend of 0.19°C per decade (Sobota et al. 2015, Kejna et al. 2012). Recently, observed positive net surface mass balance (Sobota et al. 2015), similar to other glaciers in the Antarctic Peninsula (Navarro et al. 2013, Oliva et al. 2017), may be explained by a regional cooling recorded in the last few years (Turner et al. 2016, Pętlicki et al. 2017). The temporal variation of climatic conditions is expressed in surface lowering rate since 1979, ranging from -1.7 m y^{-1} (1979-2001) to -0.5 m y^{-1} (2002-2016) (Pętlicki et al. 2017). The same pattern is noted in the frontal retreat rate that has decelerated after 2002, however the main driver of glacier front displacements is subglacial/ submarine topography at the glacier cliff (Pętlicki et al. 2017). Overall frontal changes of Ecology Glacier are moderate with the average rate ca. 0.019 km^2 y^{-1} measured in the periods 1961-1996 and 2007-2012 (Kejna et al. 1998, Sobota et al. 2015). Most ice masses of King George Island located below 400 m a.s.l. are at the pressure melting point (Blindow et al. 2010). Shallow temperature profiles confirm the existence of temperate ice on Ecology Glacier (Sobota et al. 2015).

2.2. Sampling

In total, 23 melted cryoconite holes were sampled on Ecology Glacier during fieldwork of January 2017. Cryoconite holes were located at three altitudes all within the ablation zone (Figure 1) including: 1. 128 - 142 m a.s.l. with 7 holes, 2. 168 - 172 m a.s.l. with 6 holes, and 3. 201 - 221 m a.s.l. with 9 holes. Altitudes and measurements of the depth and height of the water column were made for 22 cryoconite holes. Additional parameters, such as depth, diameter, length and width of cryoconite holes, were measured when possible (diameter for spherical holes, width and length for irregularly shaped holes) with a ruler. Cryoconite material (0.5 to 1.3 cm^3) was collected using sterile plastic Pasteur pipettes and transferred to 15 cm^3 tubes and immediately preserved with 96% ethylene alcohol. Samples were stored frozen and transported to laboratories in Poland. All 23 samples were used for faunistic analysis and organic matter measurements. For phycological and radiometric analysis, 12 and 10 samples were used, respectively. In the laboratory, after the cryoconite material had settled in the tubes (i.e., after at least 30 min), only the sediment was collected for analysis. The amount of sediment used for analysis was estimated based on the measure of the plastic tube.

2.3. Organic matter

The amount of organic matter in cryoconite was measured as a percentage weight loss through combustion at 550°C for 3 hours following drying at 50°C for 24 hours.

2.4. Microscopic observations and estimation of cyanobacteria and algae biomass

Cyanobacteria and algae were identified, counted, and measured with a Nikon Eclipse TE2000-S digital microscope. Taxa were archived through NIS (Imaging Software NIS – Elements BR on VGA). The biomass of cyanobacteria and algae for each hole was calculated as the total cell volume per unit area (standard coverslip). Mean cell volume was estimated by measuring the size of 50–100 cells for each species. To ensure accuracy of measurements, each sample was counted three to six times and thus cell concentrations (cells/cm^3) are mean values of the repeated counts. The biomass of cyanobacteria and algae for each sample was calculated as the total cell volume per unit area (standard coverslip). Every time under standard coverslip 100 µl of the cryoconite was mounted (after Yoshimura et al. 1997, modified). The taxonomy of cyanobacteria and algae is based on Hoek et al. (1995) and identification of cyanobacterial and algal species followed Krammer & Lange-Bertalot (1991a, b), Hindak (1996), Komárek & Anagnostidis (2005), Coesel & Meesters (2007), Van de Vijver et al. (2010) and John & Rindi (2015). Figure S2 contains diatom shells without chloroplast for better visibility of diagnostic features.

2.5. Microfauna extraction and identification

The material was homogenised by shaking the vials and transferred into Petri dishes (ø 8.5 cm) and entire cryoconite material was scanned for microfauna using a stereomicroscope (Olympus BZ51). On the bottom of each Petri dish, parallel thin lines at 5-mm intervals were drawn with a black marker for precise scanning (5 mm corresponds to a visible image at 30x magnification). The entire cryoconite material was scanned for microfauna using a stereomicroscope (Olympus BZ51). Subsequently, all individuals were isolated and counted. The density of animals was calculated per 1 cm^3 of cryoconite.

Representatives of the nanorchestid mite populations were cleared in KOH or Nesbitt's fluid, mounted on microslides in Hoyer's medium, examined using an Olympus BX50 phase-contrast microscope and subsequently identified following the keys of Strandtmann (1982) and Booth (1984).

To delimit rotifer species, total genomic DNA was extracted from 14 separate individuals (selected from six cryoconite holes) using the method described in Dabert et al. (2008) and Mironov et al. (2012). DNA was isolated with the DNeasy Blood and Tissue Kit (Qiagen GmbH, Hilden, Germany) following the protocol of Dabert et al. (2008). A fragment of the mitochondrial cytochrome c oxidase subunit I (COI) gene was amplified with a LCO1490 forward primer (5’-GGTCAACAAATCATAAAGATATTGG-3’) and HCO2198 reverse primer (5’-TAAACTTCAGGGTGACCAAAAAATCA-3’) (Folmer et al. 1994). Amplification of DNA fragments (PCR) for a total volume of 10 µL was carried out with the following protocol: 5 µL Type-it Microsatellite PCR Kit (Qiagen), 0.25 µM of each primer, 4 µL of the DNA template and 0.5 µL water. For PCR, a thermocycling profile with one cycle of 5 min at 95°C followed by 5 steps of 30 s each at 95°C, 60 s at 45°C, 1 min at 72°C, and 30 steps 30 s at 95°C, 60 s at 50°C and 60 s at 72°C with a final step of 5 min at 72°C for all amplicons. Samples containing single, uniform 700-bp bands were purified with exonuclease I and fast alkaline phosphatase (Fermentas). The amplicons were sequenced with the BigDye

Terminator v3.1 kit and ABI Prism 3130xl Genetic Analyzer (Applied Biosystems) following the manufacturer's instructions. The identity of COI sequences was verified with BLAST (Altschul et al. 1990) against the NCBI database. Sequences were processed in BioEdit ver. 7.2.5 (Hall 1997). Pairwise distances between nucleotide sequences were calculated via a distance model for all codon positions as implemented in MEGA 7 (Tamura et al. 2013). Delimitation and identification of the rotifer species as independently evolving entities (IEEs) was conducted employing the GMYC model (Pons et al. 2006, Fujisawa & Barraclough 2013) on both ultrametric trees constructed in BEAST 1.10.4 and Bayesian trees constructed in MrBayes 3.2, and then converted to ultrametric ones using the chronopl function in RStudio software (R Core Team 2018). GMYC analysis was performed in RStudio using the 'paran' and 'splits' packages (Supplementary Material, Appendix A, Fig. 5 and 6). The following sequences were utilised in the analysis: KJ543594-KJ543597 and KP869999 belongs to *Macrotrachela jankoi* Iakovenko et al., 2015, and KP870000 belongs to *Macrotrachela* aff. *jankoi*, and as an out group, *Floscularia melicerta* GenBank ID EU499896 (FLM) was used (Iakovenko et al. 2015). The remaining sequences are new and described in the results.

Slides with animals are deposited in the Department of Animal Taxonomy and Ecology, Adam Mickiewicz University in Poznań, Poland.

2.6. Identification and measurements of radionuclides

Owing to location and separation by cold oceanic waters of Antarctic Peninsula, it is a suitable region for analysing transport of contaminants in the environment. The Antarctic ecosystem is of great interest in estimating global environmental pollution caused by nuclear detonation tests and accidents. In order to identify radionuclides, time of their deposition and links between biotic and abiotic characteristics of supraglacial ecosystems, we identified radionuclides in glacier of Maritime Antarctic for the first time. ^{137}Cs and ^{210}Pb activity was determined with a broad energy germanium detector (BEGe), BE5030. The activities of ^{137}Cs were determined using its emission peak at 662 keV, and the emission peak at 46.6 keV was employed to determine the activities of ^{210}Pb. The activities of the ^{238}Pu, $^{239+240}$Pu, ^{241}Am, ^{234,238}U and ^{230,232}Th radionuclides were determined in 0.48 to 0.85 g of the dried samples. The samples were dissolved with mineral acids and resultant liquid samples underwent radiochemical separation and concentrations of all alpha isotopes. The procedure is extensively described elsewhere by Łokas et al. (2010, 2013, 2018). The full sequential radiochemical procedure and gamma analyses were verified employing soil reference material (IAEA 385). The results were in strong agreement with the recommended values. After further radiochemical purification procedure, the 240Pu/239Pu atomic ratio was measured through a Neptune MC-ICP-MS in accordance to Łokas et al. (2018). The reference date for ^{210}Pb and ^{137}Cs activities is 1 January 2017.

2.7. Data processing

We tested relations between continuous variables using Spearman-rank correlation (assumption for the Pearson correlation were violated). To test differences of the mean for elevations groups we used a Kruskal-Wallis rank-sum test. In case of significant results of Kruskal-Wallis, we used post hoc Dunn's test with Bonferroni-corrected alpha level. To determine central tendency we used mean and the standard error (SE) for normally distributed data, while for the variables with the distribution that deviated from normal we used the median. To asses variance for normally distributed data, we used Standard Deviation (SD), while the variables with the distribution that deviated from normal we used the Interquartile Range (IQR). Moreover, we tested evenness of a community of algae using Pielou Diversity index J based on the Shannon-Wiener index. The analysis was processed using R software (R Core Team 2018) and MVSP 3.1 software (Kovach 1985-1999).

3. Results

Mean diameter and total depth for sampled cryoconite holes on Ecology Glacier in January 2017 were 10.0±2.5, 95%CI (14.98, 16.21) and 15.9±4, 95%CI (10.48, 11.22) cm. All measurements of cryoconite holes are presented in the Table S1. The collected cryoconite consisted mostly of fine mineral grains and infrequent minute cryoconite granules (Figure S3). Cryoconite holes located in lower altitude were deeper than those located in the middle and the highest altitude (Dunn's test, $p = 0.014$ and $p = 0.002$, respectively).

Organic matter varied between 5.4% and 7.6% (*median* = 6.72, *IQR* = 0.79, *n* = 23), but without any clear gradient with the elevation (Figure S1). There was no significant correlation between organic matter content and depth of cryoconite holes (*rho* = 0.21, *df* = 20, $p = 0.14$). Likewise, there was no correlation between organic matter and total photoautotrophic biomass (*rho* = -0.077, $p = 0.8119$). However, a significant difference in means of organic matter were found between first and second group (lowest and middle altitude) of samples, with higher organic matter content in middle (Kruskal-Wallis $X^2 = 8.026$, *df* = 2, $p = 0.02$; Dunn's test $p = 0.0089$). Each cryoconite hole was characterized by relatively low biodiversity (4 to 10 species). Overall, 4 species of Chlorophyta, 4 species of Cyanobacteria, 7 species of Bacillariophyceae and 2 unidentified cysts (Figure 2, S2; Tables S2, S3) were found with relatively even distribution (Diversity index (J')) 0.347 to 1.013. In most cryoconite holes, the predominant cyanobacterial species included *Pseudanabaena frigida, Leptolyngbya* sp. 1, *Leptolyngbya* sp. 2 and *Komvophoron* sp., diatoms *Microcostatus* sp., and filamentous green algae *Klebsormidium flaccidum. Microcostatus* sp. and *Pseudanabaena frigida* domianted all holes (Figure S2). The biomass of Bacillariophyceae was significantly higher than that of Cyanobacteria (Dunn's test, $p < 0.001$) and Chlorophycae (Dunn's test, $p = 0.004$). However, there were no differences between Chlorophyta and Cyanobacteria biomass (Dunn's test, $p = 0.052$) (Figure 2, Tables S2, S3). There were no differences in total biomass of photoautotrophs among 3 elevational patches (Kruskal-Wallis $X^2 = 1.2603$, *df* = 2, $p = 0.5325$).

Among invertebrates, only 3 species of Rotifera (according to the GenBank search using BLAST algorythm and our sequence data: representatives of Philodinavidae family , relative of *Adineta* sp. and *Macrotrachela* aff. *jankoi* Iakovenko et al. 2015) and 1 species of Acari (*Nanorchestes nivalis* (Trouessart, 1914) sensu Judson (1995)) were observed, but while rotifers were present in every hole (*median* = 37, *IQR* = 60.5, *n* = 23), mites were found in 30% of the holes (*median* = 0, *IQR* = 1, *n* = 23) (Figures 3, 4, 5Table S1). Sequences for rotifers obtained in this study are deposited in GenBank under accession numbers: MT181011-MT181018; MT180985-MT180987; MT180992-MT180993. Two rotifer species did not 100% match any rotifer sequences in GenBank and may potentially be new to science (Figures 5, S5, S6). We found a marginally significant differences in densities of rotifers among elevational groups (*Kruskal-Wallis* X^2 = 6.0825, *df* = 2, *p* = 0.05, Figure 4).

Artificial and natural radionuclides observed in the samples included ^{137}Cs, $^{239+240}$Pu, ^{241}Am, ^{210}Pb, ^{234,238}U and ^{230,232}Th (Table 1, Figure S4). Significantly higher concentrations of ^{210}Pb (Dunn's test, p = *0.0131*) were associated with samples located at middle elevation than the lowest one. Isotopic ratios of ^{238}Pu/$^{239+240}$Pu, $^{239+240}$Pu/^{137}Cs ^{241}Am/$^{239+240}$Pu indicate that analysed cryoconite material could be of about 60-70 years old.

4. Discussion

Our study presents baseline data on biotic and abiotic characteristics of cryoconite holes for a glacier in Maritime Antarctica. Herein, we present data on morphology, organic matter content, primary producers, top consumers and contamination of radionuclides (proxy for long-range transport of anthropogenic originated contaminations) for cryoconite holes on Ecology Glacier sampled in 2017. Ecology Glacier is located close to the Polish Antarctic Station, "Arctowski", on King George Island (thus supporting easy logistics) and for years was in the focus of biologists (e.g., Dziewit et al. 2013, Mieczan et al. 2013, Grzesiak et al. 2015), ecologists

(Zawierucha et al. 2019), glaciologists (e.g., Bintaja 1995, Sobota et al. 2015, Pętlicki et al. 2017) and geomorphologists (Sziło et al. 2017) (Table S5). Taking into account the entirety of the literature on the biota of Ecology Glacier published until now, as well as the present study, 4 cyanobacteria taxa, 11 algae, 20 ciliates and 4 metazoans (Rotifera, Acari) have been reported (Table S4; see also subsequent results and discussion).

4.1. Cryoconite holes

The results of this study showed that cryoconite holes located at lower elevations on the Ecology Glacier have larger depth. The same phenomenon was observed in the Thule Area, (Greenland) by Gajda (1958), who showed various depths of cryoconite holes at different distances from the terminus of valley glacier. Following Gajda (1958), this effect could be caused by more energy available for melting at lower elevations of a glacier. Nevertheless, our study on Ecology Glacier and the study by Gajda (1958) cover a distance of less than 1 km. An opposite pattern but at a larger scale (4 km on valley glacier – Sermikavsak, Greenland) was shown by Gribbon (1979), who found deeper cryoconite holes in the upper part of glaciers. The results of this study and that of Gajda's (1958) may stem from local variations of their surface structure: samples were taken from visually different types of ice, as opposed to Gribbon (1979), who made measurements in each location on visually similar ice patches. Summarising the aforementioned results, cryoconite holes located further from the edge of a glacier are characterised by moving their equilibrium-depths deeper into the ice. A detailed explanation of these phenomena has been proposed by Gribbon (1979), however we did not observe this pattern, which in case of our sampling, might be related to smaller elevational gradient. Detailed formation of cryoconite holes, their forms, and depths were earlier discussed by Sharp (1949). Cryoconite holes on Ecology Glacier are smaller in diameter and size, and with thin layer of ice lid (or lacking such) during sampling, compared to those in the Antarctic McMurdo Dry Valleys

(Fountain et al. 2004). However, they are similar in size and depth as well as being open (or with very thin layer of ice) to those in Arctic Svalbard archipelago (Zawierucha et al. 2016b). This indicates that physical processes like flushing, ablation, solar radiation influencing size and shape of cryoconite holes in maritime Antarctic are similar to those found in Arctic insular climate.

4.2. Organic matter

The organic matter content in cryoconite holes from around the world can vary from <2% (e.g., Tyndal Glacier, Patagonia) to >18% (e.g., Thule Ice Ramp, Greenland) (Gerdel & Drouet 1960, Takeuchi et al. 2001a). However, an average organic matter (7%) content in cryoconite from holes (Cook et al 2015) is similar to that found in our study (6.7%). Although relatively low in our cryoconite samples, the content of organic matter has been shown to play a key role in many geochemical and biological processes in the cryosphere. Not only does it provide substrates for heterotrophic organisms, but also lowers ice albedo and binds various pollutants (Cook et al. 2015, Łokas et al. 2016, 2018). Contrary to other observations (Porazinska et al. 2004, Stibal et al. 2010, Langford et al. 2014), we did not observe elevational pattern of organic matter content. These findings might reflect relative flatness of sampling elevational gradient on Ecology Glacier, small sampling area, and possibly the timing of sampling. Significantly higher organic matter content in holes at the middle elevation is hard to explain. It is possible that opposing forces drive the productivity of organic matter (like an autochthonous and allochthonous input), and wash-out (removal) operate across elevations. Lower elevations may have more organic matter, but stronger wash-out obscures this, while wash-out is lower at higher elevations, along with lower productivity. This could result in intermediate effect.

4.3. Algae and cyanobacteria

We observed that cryoconite holes on Ecology Glacier are mostly algae-dominated systems. These findings were rather unexpected as cyanobacteria are considered cryoconite hole ecosystem engineers (Takeuchi et al. 2001a, 2001b, Hodson et al. 2008, Cook et al. 2015). They produce extracellular polymeric substances that stick together mineral and organic matter on glaciers to form granules commonly observed in Arctic and High Alpine (Takeuchi et al. 2001a, Hodson et al. 2010, Langford et al. 2014, Cook et al. 2015). We observed only small and rare cryoconite granules under a stereomicroscope, suggesting that binding properties of cyanobacteria to form granules are marginal on Ecology Glacier (Figure S3). This likely reflects communities and biomass dominated by algae over cyanobacteria. The dominance of algae over cyanobacteria in holes is generally not common, or perhaps not well known, since studies of cryoconite communities generally focus on their diversity rather than biomass (Pittino et al. 2018). We cannot exclude that inland ice sheets and small valley glaciers with significantly big inputs of dust or englacial outcropping minerals may favor cyanobacteria that bind particles and form granules; tide-water glaciers located in big fjords may receive more aqueous nutrients that favor algae. However such assumptions need further studies.

The number of taxa of cyanobacteria and algae on Ecology Glacier appears consistent with previous studies in Continental Antarctica (Wharton et al. 1981, Porazinska et al. 2004, Sommers et al. 2017). Slightly higher numbers of cyanobacterial taxa were found in previous studies on cryoconite holes in Continental Antarctic. Wharton et al. (1981) and Porazinska et al. (2004) reported seven and six taxa of cyanobacteria, respectively. However, it should be taken into account that the authors investigated few glaciers (Wharton et al. 1981, Porazinska et al. 2004), thus differences may be attributed to broader study sites. In the case of algae, Porazinska et al. (2004) did not describe them in glaciers located in the McMurdo Dry Valleys. However, Sommers et al. (2017) recently showed five taxa of algae via environmental sequencing. Among all taxa of cyanobacteria and algae revealed in our study, only one was previously found in cryoconite holes on Continental Antarctica (*Pseudanabaena frigida* (Fritsch)) by Sommers et al. (2017, 2019). We did not found any of the diatom taxa reported by

Stanisch et al. (2012) from glaciers in Antarctic Taylor Valley, who found the two dominant cryoconite hole genera, *Diadesmis* and *Muelleria*. In turn, the observed taxa of cyanobacteria and algae on Ecology Glacier corresponds better to that found on Chilean and Arctic glaciers than to Continental Antarctic cryoconite holes (Takeuchi et al. 2001a, Porazinska et al. 2004, Stibal et al. 2006, Sommers et al. 2017, 2019, Zawierucha et al. 2018).

Certain taxa of algae may be specially adapted to life within the cryoconite holes, other are opportunistic (Cameron et al. 2012, Mueller et al. 2001, Yallop and Anesio 2010). In the Arctic, where the holes are frequently hydrologically connected and lacking an ice lid, the community function and composition appears to be influenced by surface hydrology (Zawierucha et al. 2018). Ecology Glacier in maritime Antarctica might be such equivalent example.

Stanisch et al. (2013) have proven that cryoconite holes in McMurdo Dry Valleys located on glaciers with most productive hydrological basin and is closest to the Ross Sea, had the highest diatom richness. Authors claimed that glaciers at the coastal end of the Antarctic Taylor valley receive more aeolian inputs from the local area and probably collect more biological material, including diatoms, from stream beds and exposed lake shores (Stanisch et al. 2013). It supports our observations on biotic community on Ecology Glacier, which due to proximity of sea sprays bearing nutrients and delivery of mineral matter from surrounding mountains may favor diatoms.

The dominance of algae over cyanobacteria in cryoconite holes from Ecology Glacier which are mostly shallow and with thin and fragile ice lid (or without lid) potentially negatively affect cyanobacterial survivorships in quickly changing and unstable environment. Compared to Bacillariophyceae, Cyanobacteria are slow growing and more sensitive to disturbance like sediment load, flushing and mixing of water (Tang et al. 1997). Although not all Cyanobacteria may fix nitrogen directly from the atmosphere, open holes could also experience nitrogen deposition (e.g., via snow and rain precipitation) stimulating algal growth, but inhibiting cyanobacterial activities (Telling et al. 2011), especially in dynamic cryoconite holes on a small glacier. None of those mechanisms, however, have been well studied indicating the scope of work that lays ahead.

4.4. Animals

The rotifers and mites found in our samples are filter- and liquid- or suspension-feeders, feeding on bacteria, algae and perhaps detritus. For the first time on Ecology Glacier, a species of a mite (*Nanorchestes nivalis)* is fully confirmed (as a new metazoan group in cryoconite) and identified. The species have been previously reported from the Maritime Antarctic (Petermann I., Anvers I., Deception I. (South Shetland), Monroe I. (South Orkney)) and the Subantarctic (Candlemas I. (South Sandwich), South Georgia I. - Trouessart 1914, Strandtmann 1982). Antarctic nanorchestid mites have been observed in soil and mosses (e.g., Marshall & Pugh 1996, Convey & Smith 1997, Hogg & Stevens 2002, Niemi et al. 2002), but never fully confirmed in cryoconite holes (Zawierucha et al. 2015, 2019). According to Rounsevell & Greenslade (1988), *Nanorchestes* spp. are characterised by granulations in the cuticle, an adaptation to life in very humid or water habitats, where the roughness of the surface by trapping layers of air allows for respiration and protects against freezing. The ability to survive freezing up to -41°C was demonstrated by Fitzsimons (1971). *Nanorchestes antarcticus* Strandtmann, 1963 was observed to maintain normal motoric activity between -23°C to +31 °C (Fitzsimons 1971). More importantly, *Nanorchestes* spp. can feed on algae (Schuster & Schuster 1977) indicating preadaptations for living in icy ecosystems such as cryoconite holes, especially those on Ecology Glacier dominated by diatoms. Therefore, the presence of *N. nivalis* on Ecology Glacier, does not appear merely accidental, especially that more recently (2018) sediments retrieved from the same glacier contained the same mite (Zawierucha, Buda, Magowski - personal observation, Zawierucha et al. 2019). Taking into account that representatives of *N.*

nivalis are relatively small in comparison with other Antarctic mites and under stereomicroscope resemble organic granules it is easy to overlooked these animals (Figure 3 A, B). Most probably, the lack of aforementioned physiological adaptations in a vast majority of mites prevents them from colonising glaciers, and single individual findings elsewhere are rather fortuitous in cryoconite holes. A good example is a single individual of the oribatid tritonymph, *Platynothrus punctatus* (C.L. Koch, 1879) (Acari: Oribatida), which was detected only on one (Hansbreen) among six glaciers on Svalbard, indicating an accidental windblown faunal element (Olszanowski - personal observation). We confirmed presence of various instars of mites in cryoconite oles on Ecology Glacier during two seasons. Definitely, our results shows that *N. nivalis* on Ecology Glacier can be persistent resident in cryoconite holes.

Invertebrates like tardigrades and rotifers are common in cryoconite holes in polar regions acting as top consumers (Zawierucha et al. 2015, 2018, 2019). Rotifer diversity found on Ecology Glacier is lower than in other reports on cryoconite holes in the Arctic, and higher than in the Continental Antarctic. Porazinska et al. (2004) observed 2 rotifer species on glaciers in the McMurdo Dry Valleys, while De Smet and Van Rompu (1994) found 7 species of rotifers on a glacier on Svalbard. Densities of rotifers on Ecology Glacier are greater than in the McMurdo Dry Valleys (Porazinska et al. 2004) and comparable with those in the Arctic (Zawierucha et al. 2018).

Acutuncus antarcticus (Richters, 1904) is a common Antarctic tardigrade found previously in cryoconite holes (Cesari et al. 2016, Porazinska et al. 2004), however, not a single specimen of any tardigrade species was found in our study, nor in samples collected in 2018 (personal observation, Zawierucha et al. 2019). On Ecology Glacier, a single specimen of *A. antarcticus* was detected in a cryoconite hole material collected by J. Grzesiak in 2009. Their absence remains unclear.

4.5. Radionuclides

The main sources of plutonium in the Southern Hemisphere were French and British nuclear tests in the Southern Pacific (Mururoa), Australia (Woomera) and Indian Ocean (Monte Bello) areas. Another and most significant source of ^{238}Pu (90%) in the Antarctic is accidental burn-up of the SNAP-9A satellite in the atmosphere over Madagascar in 1964. In addition, the ^{238}Pu/$^{239+240}$Pu ratios in few samples suggest contributions from local or perhaps more recent trace of Pu of a different origin.

Occurrence of ^{241}Am is related to directly by nuclear explosions, and its environmental activity is increasing, because of the decay product of the fallout beta emitter ^{241}Pu ($T_{1/2}$ = 14.4 yr). Therefore the ^{241}Am/$^{239+240}$Pu ratio can rise to the range of 0.32 - 0.42. The ratio can be also as high in the Southern Hemisphere as 0.80 (2017) based on the high-yield US nuclear tests in 1953 at Bikini Atoll, Marshal Island and Enewetak Atoll (Jia et al. 1999). It was calculated from the ^{241}Pu/$^{239+240}$Pu activity ratio in 1953. To what extent these pollutants affect cryoconite communities is still unknown, but warrants further research.

There is ongoing interest in radioactivity of Antarctic terrestrial and marine ecosystems (Roos et al. 1994, Jia et al. 1999, 2000, Desideri et al. 2003, Giuliani et al. 2003, Mietelski et al. 2000, 2008, Szufa et al. 2018), including ice shelves (Koide et al. 1979). Radionuclide activity concentrations in cryoconite holes may reach much higher values than in surrounding glacier habitats including mosses and lichens. Recently cryoconite was suggested as efficient accumulator of radionuclides in the high mountain regions due to being significantly more radioactive than the matrices usually adopted for the environmental monitoring of radioactivity (Łokas et al. 2018, Baccolo et al. 2020). Indeed, our results of radioactivity of cryoconite from Ecology Glacier indicate the same phenomenon for Antarctic region. Prolonged exposure of cryoconite to atmospheric dust and the presence of cryophilic organisms and organic matter may lead to a build-up of radionuclide levels (Figure 5). Comparing our data with the maximum activity concentrations of ^{137}Cs in mosses (50 Bq kg^{-1}), lichens (162 Bq kg^{-1}) (Jia et al. 1999) and soils (30 Bq kg^{-1}) (Schuller et al. 1993), values from cryoconite holes are 2 to 3 times higher. A similar trend was observed in activity concentrations of ^{238}Pu, $^{239+240}$Pu and ^{241}Am in mosses (0.21 Bq kg^{-1}, 0.91 Bq kg^{-1}, 0.61 Bq kg^{-1}), lichens (0.75 Bq kg^{-1}, 4.6 Bq kg^{-1}, 1.9 Bq kg^{-1}) and soils (0.003 Bq kg^{-1}, 0.019 Bq kg^{-1}, 0.010 Bq kg^{-1}) (Jia et al. 1999).

Studies around the world indicate that radionuclides are actively trapped in cryoconite and ice. First studies on artificial radionuclides content on glaciers were conducted by Jaworowski et al. (1978) who showed that artificial radioactive isotopes are stored in ice. Cryoconite is a kind of biogenic sediment formed when combination of the processes acting in the supraglacial zone leads to mixing and interaction of mineral particulate matter of local and remote origin with organic compounds, bacteria and algae (Takeuchi et al. 2010, 2011 a, b). We suspect that anthropogenic (artificial) radionuclides stored in ice, during melting are released and accumulate in microbes and fungi and up the food chain in microinvertebrates. When viruses lyse cells, they release radionuclides into the cryoconite again. We found that the highest contents of lead, cesium and plutonium were observed in samples with highest organic matter that may effectively accumulate and recycle artificial radionuclides (Łokas et al. 2016). Values of activity ratios (Łokas et al. 2018, Baccolo et al. 2017) in cryoconite collected from holes suggest their yearly biogeochemical recycling, also on Ecology Glacier for more than 70 years when first artificial radionuclides appeared (Figure 6 5). Presence of artificial radionuclides on Ecology Glacier is indicator that mineral material in cryoconite cannot be old englacial origin and most probably derived within last 70 years (windblown from mountains and forefields). High level of radionuclides could be related to algae and cyanobacteria, but effects of such bioaccumulation on glaciers needs closer attention.

5. Summary

- We observed variation of cryoconite holes depth, organic matter content, Rotifera counts as well as lead-210 concentration. Such heterogeneity may result from the specific morphology of the glacier surface, distance from terminus (potential transport of aerosols) as well as altitude.
- Depth of cryoconite holes on Ecology Glacier in January 2017 was related to elevation and increased towards the glacier margin.
- Distribution of organic matter content was homogenous and unrelated to hole morphology.
- Seventeen taxa of algae and cyanobacteria, three taxa of rotifers, and one of acari were found.
- Cryoconite holes on Ecology Glacier were dominated by Bacillariophyceae. This predominance most probably prevents formation of glacier cryoconite granules.
-, A suspension-feeding mite species was observed for the first time in cryoconite holes.
- Densities of animals were more similar to Arctic than to continental Antarctic cryoconite holes.
- Radionuclides have been likely stored on Ecology Glacier since 1950s and these radionuclides are most probably recycled in cryoconite each season by microbial communities.
- Taking into account all the literature and recently presented data, Ecology Glacier may constitute robust glacier model for comparison of glacial biodiversity between South America and Continental Antarctic.
- All biotic characteristics of cryoconite holes on Ecology glacier presented in this study are specific functions of time and space (locality) of sampling in Maritime Antarctic.

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References

Altschul, S.F., Gish, W., Miller, W., Myers, E.W. & Lipman, D.J. (1990). Basic local alignment search tool. Journal of Molecular Biology, 215, 403-410. http://dx.doi.org/10.1016/S0022-2836(05)80360

Anesio, A.M., Hodson, A.J., Fritz, A., Psenner, R. & Sattler, B. (2009). High microbial activity on glaciers: importance to the global carbon cycle. Global Change Biology, 15, 955-960.

Anesio, A.M. & Laybourn-Parry, J. (2012). Glaciers and ice sheets as a biome. Trends in Ecology & Evolution, 27, 219-225.

Artaxo, P., Rabello, M.L., Maenhaut, W. & Grieken, R. V. (1992). Trace elements and individual particle analysis of atmospheric aerosols from the Antarctic Peninsula. Tellus B, 44, 318-334.

Baccolo, G., Łokas, E., Gaca, P., Massabò, D., Ambrosini, R., Azzoni, R.S., Clason, C., Di Mauro, B., Franzetti, A., Nastasi, M., Prata, M., Prati, P., Previtali, E., Delmonte, B., Maggi, V. (2020). Cryoconite: an efficient accumulator of radioactive fallout in glacial environments. Cryosphere, 14, 657-672.

Baccolo, G., Di Mauro, B., Massabò, D., Clemenza, M., Nastasi, M., Delmonte, B., Prata, M., Prati, P., Previtali, E. & Maggi, V. (2017). Cryoconite as a temporary sink for anthropogenic species stored in glaciers. Scientific reports, 7, p.9623.

Bagshaw, E.A., Tranter, M., Fountain, A.G, Welch, K.A, Basagic, H.J. & Lyons, W.B. (2007). Biogeochemical evolution of cryoconite holes on Canada Glacier, Taylor Valley, Antarctica. Journal of Geophysical Research, 112, G04S35.

Bagshaw, E.A., Tranter, M., Fountain, A.G., Welch, K.A., Basagic, H.J. & Lyons, W,B. (2013). Are cryoconite holes a significant source of C, N and P to the downstream depauperate ecosystems of the McMurdo Dry Valleys? Arctic Antarctic and Alpine Research, 45, 1-15.

Bagshaw, E.A., Tranter, M., Wadham, J.L,, Fountain, A.G. & Mowlem, M. (2011). High-resolution monitoring reveals dissolved oxygen dynamics in an Antarctic cryoconite hole. Hydrological Processes, 25, 2868-2877.

Bintanja, R. (1995). The local surface energy balance of the Ecology Glacier, King George Island, Antarctica: measurements and modelling. Antarctic Science, 7, 315-325.

Birkenmajer, K., Francalanci, L. & Peccerillo, A. (1991). Petrological and geochemical constraints on the genesis of Mesozoic–Cenozoic magmatism of King George Island, South Shetland Islands, Antarctica. Antarctic Science, 3, 293-308.

Blindow, N., Suckro, S., Ruckamp, M., Braun, M., Breuer, B., Saurer, H., Simoes, J., Schindler, M. & Lange, M. (2010). Geometry and thermal regime of the King George Island ice cap, Antarctica, from GPR and GPS. Annals of Glaciology, 51, 103-109.

Braun, M. & Gossmann, H. (2002). Glacial Changes in the Areas of Admiralty Bay and Potter Cove, King George Island, Maritime Antarctica. Ecological Studies, Vol. 154, Beyer,

L. & Bolter, M. (eds.) Geoecology of Antarctic Ice-Free Coastal Landscapes Springer-Verlag Berlin Heidelberg 2002.

Braun, M., Saurer, H., Vogt, S., Simões, J.C. & Goßmann, H. (2001). The influence of large-scale atmospheric circulation on surface energy balance on the ice cap of King George Island. International Journal of Climatology, 21, 21-36.

Booth, R.G. (1984). A new species of mite in the genus *Nanorchestes* (Acari, Prostigmata) from Signy Island, South Orkney Islands. British Antarctic Survey Bulletin, 63, 111-116.

Cameron, K.A., Hodson, A.J. & Osborn, A.M. (2012). Structure and diversity of bacterial, eukaryotic and archaeal communities in glacial cryoconite holes from the Arctic and the Antarctic. FEMS Microbiology Ecology, 82, 254-67.

Cesari, M., McInnes, S., Bertolani, R., Rebecchi, L. & Guidetti, R. (2016). Genetic diversity and biogeography of the south polar water bear *Acutuncus antarcticus* (Eutardigrada: Hypsibiidae) – evidence that it is a truly pan-Antarctic species. Invertebrate Systematics, 30, 635-649.

Coesel, P.F.M. & Meesters, J. (2007). Desmids of the Lowlands. Mesotaeniaceae and Desmidiaceae of the European Lowlands. KNNV Publishing, 351 pp.

Convey, P. (2013). Maritime Antarctic Climate Change: Signals from Terrestrial Biology. Antarctic Research Series, 145-158. http://dx.doi:10.1029/ar079p0145

Convey, P. & Smith, R.I.L. (1997). The terrestrial arthropod fauna and its habitats in northern Marguerite Bay and Alexander Island, maritime Antarctic. Antarctic Science, 9, 12-26.

Cook, J., Edwards, A., Takeuchi, N. & Irvine-Fynn, T. (2015). Cryoconite. The dark biological secret of the cryosphere. Progress in Physical Geography, 40, 66–111.

Dabert, J., Ehrnsberger, R. & Dabert, M. (2008). *Glaucalges tytonis* sp. nov. (Analgoidea: Xolalgidae) from the barn owl *Tyto alba* (Strigiformes: Tytonidae): compiling morphology with DNA barcode data for taxa descriptions in mites (Acari). Zootaxa, 1719, 41-52.

Dastych, H., Kraus, H.J. & Thaler, K. (2003). Redescription and notes on the biology of the glacier tardigrade *Hypsibius klebelsbergi* Mihelcic, 1959 (Tardigrada), based on material from Ötztal Alps, Austria. Mitteilungen Hamburgisches Zoologisches Museum und Institut, 100, 77-100.

De Smet, W.H. & Van Rompu, E.A. (1994). Rotifera and Tardigrada from some cryoconite holes on a Spitsbergen (Svalbard) glacier. Belgian Journal of Zoology, 124, 27-27.

Desideri, D., Giuliani, S., Testa, C. & Triulzi, C. (2003). 90Sr, 137Cs, 238Pu, 239+240Pu and 241Am levels in terrestrial and marine ecosystems around the Italian base in Antarctica. Journal of Radioanalytical and Nuclear Chemistry, 258, 221-225.

Dziewit, L., Grzesiak, J., Ciok, A., Nieckarz, M., Zdanowski, M.K. & Bartosik, D. (2013). Sequence determination and analysis of three plasmids of *Pseudomonas* sp. GLE121, a psychrophile isolated from surface ice of Ecology Glacier (Antarctica). Plasmid, 70, 254-262.

Edwards, A., Rassner, S.M., Anesio, A.M., Worgan, H.J., Irvine-Fynn, T.D., Wyn Williams, H., Sattler, B. & Wyn Griffith, G. (2013). Contrasts between the cryoconite and ice-marginal bacterial communities of Svalbard glaciers. Polar Research, 32, 19468.

Ferron, F.A., Simões, J.C., Aquino, F.E. & Setzer, A. W. (2004). Air temperature time series for King George Island, Antarctica. Pesquisa Antártica Brasileira, 4, 155-169.

Fitzsimons, J.M. (1971). Temperature and three species of Antarctic arthropods. Pacific Insects Monographs, 25, 127-135.

Folmer, O., Black, M., Hoeh, W., Lutz, R. & Vrijenhoek, R. (1994). DNA primers for amplification of mitochondrial cytochrome c oxidase subunit I from diverse metazoan invertebrates. Molecular Marine Biology and Biotechnology, 3, 294-299.

Fountain, A., Tranter, M., Nylen, T. H., Lewis, K. J., & Mueller, D. R. (2004). Evolution of cryoconite holes and their contribution to melt water runoff from glaciers in the McMurdo Dry Valleys, Antarctica. Journal of Glaciology, 50, 35-45.

Franzetti, A., Navarra, F., Tagliaferri, I., Gandolfi, I., Bestetti, G., Minora, U., Azzoni, R.S., Diolaiuti, G., Smiraglia, C. & Ambrosini, R. (2017). Potential sources of bacteria colonizing the cryoconite of an Alpine glacier. PloS one, 12, e0174786.

Fujisawa, T. & Barraclough, T.G. (2013). Delimiting species using single-locus data and the generalized mixed Yule coalescent approach: a revised method and evaluation on simulated data sets. Systematic Biology, 62, 707-724.

Gajda, R.T. (1958). Cryoconite phenomena on the Greenland ice cap in the Thule Area. Canadian Geographer, 3, 35-44.

Gerdel, R.W. & Drouet, F. (1960). The cryoconite of the Thule Area, Greenland. Transactions of the American Microscopical Society, 79, 256-272.

Giuliani, S., Triulzi, C. & Vaghi, M. (2003). Anthropogenic radionuclides in plants, animals and their environments in Antarctica. Морський екологічний журнал 2, 551.35:539.163.

Gribbon, P.W.F. (1979). Cryoconite holes on Sermikavsak, west Greenland. Journal of Glaciology, 22, 177-181.

Grzesiak, J., Zdanowski, M.K., Górniak, D., Świątecki, A., Alksandrzak-Piekarczyk, T., Szatraj, K., Sasin-Kurowska, J. & Nieckarz, M. (2015). Microbial community changes along the Ecology Glacier ablation zone (King George Island, Antarctica). Polar Biology, 38, 2069-2083. https://doi.org/10.1007/s00300-015-1767-z

Hall, T.A. (1997). BIOEDIT: a user-friendly biological sequence alignment editor and analysis program for Windows 95/98/NT. Nucleic Acids Symposium Series, 41, 95-98.

Hindak, F. (1996). Key to the unbranched filamentous green algae (Ulotrichineae, Ulotrichales, Chlorophyceae). Bulletin Slovenskej botanickej spoločnosti pri SAV. Bratislava, pp. 77.

Hodson, A., Anesio, A.M., Tranter, M., Fountain, A., Osborn, M., Priscu, J., Laybourn-Parry, J. & Sattler, B. (2008). Glacial ecosystems. Ecological monographs, 78, 41-67.

Hodson, A., Bøggild, C., Hanna, E., Huybrechts, P., Langford, H., Cameron, K. & Houldsworth, A. (2010). The cryoconite ecosystem on the Greenland ice sheet. Annals of Glaciology, 51, 123-129.

Hodson, A., Nowak, A., Sabacka, M., Jungblut, A., Navarro, F., Pearce, D., Ávila-Jiménez, M.L., Convey, P. & Vieira, G. (2017). Climatically sensitive transfer of iron to maritime Antarctic ecosystems by surface runoff. Nature communications, 8, p.14499.

Hoek, C., Mann, D.G. & Johns, H.M. (1995). Alga: an introduction to phycology. Great Britain at University Press, Cambridge, 623 pp.

Hogg, I.D. & Stevens, M.I. (2002). Soil fauna of Antarctic coastal landscapes. In: Geoecology of Antarctic ice-free coastal landscapes, Springer, Berlin, Heidelberg, pp. 265-280.

Iakovenko, N.S., Smykla, J., Convey P., Kašparová, E., Kozeretska, I.A., Trokhymets, V., Dykyy, I., Plewka, M., Devetter, M., Duriš, Z. & Janko, K. (2015). Antarctic bdelloid rotifers: diversity, endemism and evolution. Hydrobiologia, 761, 5-43.

Jaworowski, Z., Kownacka, L., Grotowski, K. & Kwiatkowski K. (1978). LEAD-210 from Nuclear Explosions in the Environment. Nuclear Technology, 37, 159-166

Jia, G., Triulzi, C., Marzano, F.N., Belli, M., Sansone, U. & Vaghi, M. (1999). Plutonium, ^{241}Am, ^{90}Sr, and ^{137}Cs concentrations in some antarctic matrices. Biological trace element research, 71, 349-357.

Jia, G., Triulzi, C., Marzano, F.N., Belli, M. & Vaghi, M. (2000). The fate of plutonium, ^{241}Am, ^{90}Sr and ^{137}Cs in the Antarctic ecosystem. Antarctic Science, 12, 141-148.

John D.M. & Rindi F. (2015). Freshwater Algae of North America. Ecology and Classification. In: Aquatic Ecology, 375-427.

Judson, M. (1995). Identity of the Antarctic mite *Gainia nivalis* Trouessart (Acari, Nanorchestidae). Bulletin du Muséum national d'histoire naturelle, 17, 83-86.

Kejna, M., Láska, K. & Caputa, Z. (1998). Recession of Ecology Glacier (King George Island) in the period 1961–1996. Polish Polar Studies, 121-128.

Kejna, A., Sobota, I. & Araźny, A. (2012). Warunki meteorologiczne w rejonie Stacji Arctowskiego (Wyspa Króla Jerzego, Antarktyka) w okresie 19.01-19.02.2012 roku. Problemy Klimatologii Polarnej, 103-116.

Koide, M., Michel, R., Goldberg, E.D., Herron, M.M. & Langway Jr, C.C. (1979). Depositional history of artificial radionuclides in the Ross Ice Shelf, Antarctica. Earth and Planetary Science Letters, 44, 205-223.

Komárek, J. & Anagnostidis, K. (2005). Cyanoprocaryota; Oscillatoriales II. In: Büdel, A.B., Krammer, K.L. & Lange-Bertalot, H. (1986). Bacillariophyceae 2/1. Naviculaceae. In: H. Ettl, J. Krienitz, G. Gärtner, & Schagerl, M. (eds). Süβwasserflora von Mitteleuropa, 19.2, Spektrum Akademischer Verlag, pp. 759.

Krammer, K. & Lange-Bertalot, H. (1991a). Bacillariophyceae 2/3. Centrales, Fragilariaceae, Eunotiaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (eds). Süβwasserflora von Mitteleuropa, Gustav Fischer Stuttgart-New York, pp. 576.

Krammer, K. & Lange-Bertalot, H. (1991b). Bacillariophyceae 2/4. Achnanthaceae, Kritische, Ergänzungen zu Navicula (Lineolatae) und Gomphonema Gesamtliteraturaturverzeichnis. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (eds). Süβwasserflora von Mitteleuropa, Gustav Fischer Stuttgart-New York, pp. 437.

Kovach, W.L. (1985–1999). MVSP PLUS version 3.1. Pentraeth, UK.

Knap, W.H., Oerlemans, J. & Cabée, M. (1996). Climate sensitivity of the ice cap of King George Island, South Shetland Islands, Antarctica. Annals of Glaciology, 23, 154-159.

Langford, H.J., Irvine-Fynn, T.D.I., Edwards, A., Banwart, S.A. & Hodson, A.J. (2014). A spatial investigation of the environmental controls over cryoconite aggregation on Longyearbreen glacier, Svalbard. Biogeosciences, 11, 5365-5380.

Łokas, E., Mietelski, J.W., Ketterer, M.E., Kleszcz, K., Wachniew, P., Michalska, S. & Miecznik, M. (2013). Sources and vertical distribution of ^{137}Cs, ^{238}Pu, $^{239+240}$Pu and ^{241}Am in peat profiles from southwest Spitsbergen. Applied Geochemistry, 28, 100-108.

Łokas, E., Mietelski, J.W., Kleszcz, K. & Tomankiewicz, E. (2010). A sequential procedure for determining ^{238}Pu, $^{239+240}$Pu, ^{241}Am, ^{90}Sr, U and Th activities in soils and peats from Spitsbergen. Nukleonika, 55, 195-199.

Łokas, E., Zaborska, A., Kolicka, M., Różycki M. & Zawierucha, K. (2016). Accumulation of atmospheric radionuclides and heavy metals in cryoconite holes on an Arctic glacier. Chemosphere, 160, 162-172, https://doi.org/10.1016/j.chemosphere.2016.06.051

Łokas, E., Zaborska, A., Sobota, I., Gaca, P., Milton, A., Kocurek, P. & Cwanek, A. (2019). Airborne radionuclides and heavy metals in High Arctic terrestrial environment as the indicators of sources and transfers of contamination. The Cryosphere Discussions. https://doi.org/10.5194/tc-2019-34

Łokas, E., Zawierucha, K., Cwanek, A., Szufa, K., Gaca, P., Mietelski, J.W. & Tomankiewicz, E. (2018). The sources of high airborne radioactivity in cryoconite holes from the Caucasus (Georgia). Scientific Reports, 8, 10802, https://doi.org/10.1038/s41598-018-29076-4

Marshall, D.J. & Pugh, P.J. (1996). Origin of the inland Acari of Continental Antarctica, with particular reference to Dronning Maud Land. Zoological Journal of the Linnean Society, 118, 101-118.

Marsz A.A. and Styszyńska A. (eds.) 2000. The main features of the climate region the Polish Antarctic Station H. Arctowski (West Antarctica, South Shetland Islands, King George Island). Wyższa Szkoła Morska, Gdynia, 1-264 (in Polish)

Martianov, V. & Rakusa-Suszczewski, S. (1989). Ten years of climate observations at the Arctowski and Bellingshausen stations (King George Is., South Shetlands, Antarctica). Global change, regional research centres, 80-87.

Mieczan, T., Górniak, D., Świątecki, A., Zdanowski, M., Tarkowska, M. & Adamczuk, M. (2013). Vertical microzonation of ciliates in cryoconite holes in Ecology Glacier, King George Island. Polish Polar Research, 34, 201-212.

Mietelski, J., Gaca, P. & Olech, M. (2000). Radioactive contamination of lichens and mosses collected in South Shetlands and Antarctic Peninsula. Journal of Radioanalytical and Nuclear Chemistry, 245, 527-537.

Mietelski, J.W., Olech, M.A., Sobiech-Matura, K., Howard, B.J., Gaca, P., Zwolak, M., Błażej, S. & Tomankiewicz, E. (2008). ^{137}Cs, ^{40}K, ^{238}Pu, $^{239+240}$Pu and ^{90}Sr in biological samples from King George Island (Southern Shetlands) in Antarctica. Polar Biology, 31, 1081-1089.

Mironov, S.V., Dabert, J. & Dabert, M. (2012). A new feather mite species of the genus *Proctophyllodes* Robin, 1877 (Astigmata: Proctophyllodidae) from the Long–tailed Tit *Aegithalos caudatus* (Passeriformes: Aegithalidae) – morphological description with DNA barcode data. Zootaxa, 3253, 54-61.

Mueller, D.R., Vincent, W.F., Pollard, W.H., & Fritsen. C.H. (2001). Glacial cryoconite ecosystems: a bipolar comparison of algal communities and habitats Nova Hedwigia, 123, 173-97.

Navarro, F., Jonsell, U., Corcuera, M. & Martin-Espanol, A. (2013). Decelerated mass loss of Hurd and Johnsons Glaciers, Livingston Island, Antarctic Peninsula. Journal of Glaciology, 59, 115-128.

Niemi, R., Uusitalo, M. & Lintinen, P. (2002). *Nanorchestes* Topsent and Trouessart, 1890 and *Eupodes* Koch, 1836 (Acari: Prostigmata) from Vestfjella mountain range, Antarctica. Entomologica Fennica, 13, 236-240.

Oliva, M., Navarro, F., Hrbáček, F., Hernández, A., Nývlt, D., Pereira, P., Ruiz-Fernández, J. & Trigo, R. (2017). Recent regional climate cooling on the Antarctic Peninsula and associated impacts on the cryosphere. Science of the Total Environment, 580, 210-223.

Pętlicki, M., Sziło, J., MacDonell, S., Vivero, S. & Bialik R. (2017). Recent Deceleration of the Ice Elevation Change of Ecology Glacier (King George Island, Antarctica). Remote Sensing, 9, 520, https://doi:10.3390/rs9060520

Pittino, F., Maglio, M., Gandolfi, I., Azzoni, R.S., Diolaiuti, G., Ambrosini, R. & Franzetti, A. (2018). Bacterial communities of cryoconite holes of a temperate alpine glacier show both seasonal trends and year-to-year variability. Annals of Glaciology, 1-9.

Pons, J., Barraclough, T.G., Gomez-Zurita, J., Cardoso, A., Duran, D.P., Hazell, S., Kamoun, S., Sumlin, W.D. & Vogler, A.P. (2006). Sequence-based species delimitation for the DNA taxonomy of undescribed insects. Systematic Biology, 55, 595-609.

Porazinska, D.L., Fountain, A.G., Nylen, T.H., Tranter, M., Virginia, R.A. & Wall, D.H. (2004). The biodiversity and biogeochemistry of cryoconite holes from McMurdo Dry Valley glaciers, Antarctica. Arctic, Antarctic, and Alpine Research, 36, 84-91.

Quayle, W.C., Peck, L.S., Peat, H., Ellis-Evans, J.C. & Harrigan, P.R. (2002). Extreme Responses to Climate Change in Antarctic Lakes. Science, 295, 645, https://doi: 10.1126/science.1064074

R Core Team (2018) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org

Rakusa-Suszczewski, S., Mietus, M. & Piasecki, J. (1993). Weather and climate. In: Rakusa-Suszczewski, S. (eds). The maritime Antarctic coastal ecosystem of Admiralty Bay. Warsaw: Polish Academy of Sciences, pp. 19-25.

Robinson, S.A., Wasley, J. & Tobin, A.K. (2003). Living on the edge-plants and global change in continental and maritime Antarctica, Global Change Biology, 9, 1681-1717.

Roos, P., Holm, E., Persson, R.B.R., Aarkrog, A. & Nielsen, S.P. (1994). Deposition of ^{210}Pb, ^{137}Cs, $^{239+240}$Pu, ^{238}Pu, and ^{241}Am in the Antarctic Peninsula Area. Journal of environmental radioactivity, 24, 235-251.

Rounsevell, D.E. & Greenslade, P. (1988). Cuticle structure and habitat in the *Nanorchestidae* (Acari: Prostigmata). Hydrobiologia, 165, 209-212.

Samui, G., Antony, R., Thamban M. (2018). Chemical characteristics of hydrologically distinct cryoconite holes in coastal Antarctica. Annals of Glaciology. https://doi: 10.1017/aog.2018.30

Schuller, P., Løvengreen, C. & Handl, J. (1993). 137Cs concentration in soil, prairie plants, and milk from sites in southern Chile. Health Physics, 64, 157-161.

Schuster, R. & Schuster, U. (1977). Ernahrungs-und fortpflanzungs-biologische Studien an der Milbenfamilie Nanorchestidae. Zoologischer Anzeiger, 199, 89-94.

Segawa, T., Yonezawa, T., Edwards, A., Akiyoshi, A., Tanaka, S., Uetake, J., Irvine-Fynn, T., Fukui, K., Li, Z. & Takeuchi, N. (2017). Biogeography of cryoconite forming cyanobacteria on polar and Asian glaciers. Journal of biogeography, 44, 2849-2861.

Sharp, R.P. (1949). Studies of superglacial debris on valley glaciers. American Journal of Science, 247, 289-315.

Smith, J.T., Appleby, P.G., Hilton, J. & Richardson, N. (1997). Inventories and fluxes of ^{210}Pb, ^{137}Cs and ^{241}Am determined from the soils of three small catchments in Cumbria, UK. Journal of Environmental Radioactivity, 37, 127-142.

Sobota, I., Kejna, M. & Araźny, A. (2015). Short-term mass changes and retreat of the Ecology and Sphinx glacier system, King George Island, Antarctic Peninsula. Antarctic Science, 27, 500-510.

Sommers, P., Darcy, J.L., Gendron, E.M.S., Stanish, L.F., Bagshaw, E.A., Porazinska, D.L. & Schmidt, S.K. (2017). Diversity patterns of microbial eukaryotes mirror those of bacteria in Antarctic cryoconite holes. FEMS Microbiology Ecology, 94. https://doi: 10.1093/femsec/fix167

Sommers. P., Darcy, J.L., Porazinska, D.L., Gendron, E.M.S., Fountain, A.G., Zamora, F., Vincent, K., Cawley, K.M., Solon, A.J., Vimercati, L., Ryder, J. & Schmidt, S.K. (2019). Comparison of microbial communities in the sediments and water columns of frozen cryoconite holes in the McMurdo Dry Valleys. Antarctica. Frontiers in Microbiology 10. https://doi.org/10.3389/fmicb.2019.00065

Stanish, L.F., Bagshaw, E.A., McKnight, D.M., Fountain A.G., Tranter, M. 2013. Environmental factors influencing diatom communities in Antarctic cryoconite holes. Environmental Research Letters, 8, 045006. doi:10.1088/1748-9326/8/4/045006

Stibal, M., Bradley, J.A., Edwards, A., Hotaling, S., Zawierucha, K., Rosvold, J., Lutz, S., Cameron, K.A., Mikucki, J.A., Kohler, T.J., Šabacká, M. & Anesio, A.M. (2020) Glacial ecosystems are essential to understanding biodiversity responses to glacier retreat. Nature Ecology & Evolution, https://doi.org/10.1038/s41559-020-1163-0.

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., Schostag, M., Cameron, K.A., Hansen, L.H., Chandler, D.M., Wadham, J.L. & Jacobsen, C.S. (2015). Different bulk and active bacterial communities in cryoconite from the margin and interior of the Greenland ice sheet. Environmental microbiology reports, 7, 293-300.

Stibal, M., Šabacká, M. & Kaštovská, K. (2006). Microbial communities on glacier surfaces in Svalbard: impact of physical and chemical properties on abundance and structure of cyanobacteria and algae. Microbial Ecology, 52, 644.

Strandtmann, R.W. (1982). Notes on *Nanorchestes* V. Two new species of *Nanorchestes* (Acari: Nanorchestidae) from the Antarctic Peninsula and South Atlantic islands. Pacific Insects, 24, 252-258.

Sziło, J. & Bialik, R.J. (2017). Bedload transport in two creeks at the ice-free area of the Baranowski Glacier, King George Island, West Antarctica, Polish Polar Research, 38, 21-29.

Szufa, K.M., Mietelski, J.W., Anczkiewicz, R., Sala, D. & Olech, M.A. (2018). Variations of plutonium isotopic ratios in Antarctic ecosystems. Journal of radioanalytical and nuclear chemistry, 318, 1511-1518.

Van de Vijver, B., Ector, L., de Haan, M. & Zidarova, R. (2010). The genus *Microcostatus* in the Antarctic region. Diatom Research, 25, 417-429.

Tamura, K., Stecher, G., Peterson, D., Filipski, A. & Kumar, S. (2013). MEGA6: Molecular Evolutionary Genetics Analysis Version 6.0. Molecular Biology and Evolution, 30, 2725-2729. http://dx.doi.org/10.1093/molbev/mst197

Takeuchi, N., Kohshima, S., Goto-Azuma, K. & Koerner, R.M. (2001b). Biological characteristics of dark colored material (cryoconite) on Canadian Arctic glaciers (Devon and Penny ice caps). Proceedings of the Memoirs of the National Institute of Polar Research, Special Issue, 54, 495-505.

Takeuchi, N., Kohshima, S., Shiraiwa, T. & Kubota, K. (2001a). Characteristics of cryoconite (surface dust on glaciers) and surface albedo of a Patagonian glacier, Tyndall Glacier, Southern Patagonia Icefield, Bulletin of Glaciological Research, 18, 65-69.

Takeuchi, N., Nishiyama, H. & Li, Z. (2010). Structure and formation process of cryoconite granules on Ürümqi glacier No. 1, Tien Shan, China. Annals of Glaciology, 51, 9-14.

Tang, E.P., Tremblay, R. & Vincent, W.F. (1997). Cyanobacterial dominance of polar freshwater ecosystems: are high-latitude mat-formers adapted to low temperature? Journal of Phycology, 33, 171-181.

Tedstone, A.J., Bamber, J.L., Cook, J.M., Williamson, C.J., Fettweis, X., Hodson, A.J. & Tranter, M. (2017). Dark ice dynamics of the south-west Greenland Ice Sheet. The Cryosphere, 11, 2491-2506.

Telling, J., Anesio, A.M., Tranter, M., Stibal, M., Hawkings, J., Irvine-Fynn, T., Hodson, A., Butler, C. & Wadham, J. (2012). Controls on the autochthonous production and respiration of organic matter in cryoconite holes on high Arctic glaciers. Journal of Geophysical Research: Biogeosciences, 117(G1).

Trouessart, E. (1914). Acariens. Deuxième Expédition Antarctique Française (1908-1910), commandée par le Dr. Jean Charcot. Sciences naturelles. Documents scientifique. Masson, Paris, pp. 1-16.

Turner, J., Lu, H., White, I., King, J., Phillips, T., Hosking, J., Bracegirdle, T., Marshall, G., Mulvaney, R. & Deb, P. (2016). Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. Nature, 535, 411-415.

Wharton Jr, R.A., Vinyard, W.C., Parker, B.C., Simmons Jr G.M. & Seaburg, K.G. (1981). Algae in cryoconite holes on Canada Glacier in Southern Victorialand, Antarctica. Phycologia, 20, 208-211.

Wharton Jr, R.A., McKay, C.P., Simmons Jr, G.M. & Parker, B.C. (1985). Cryoconite holes on glaciers. BioScience, 35, 499-503.

Williamson, C.J., Anesio, A.M., Cook, J., Tedstone, A., Poniecka, E., Holland, A., Fagan, D., Tranter, M. & Yallop, M.L. (2018). Ice algal bloom development on the surface of the Greenland Ice Sheet. FEMS microbiology ecology, 94, fiy025.

Yallop, M.L. & Anesio, A.M. (2010). Benthic diatom flora in supra-glacial habitats: a generic level comparison Annales of Glaciology, 51, 15-22.

Yoshimura, Y., Kohshima, S. & Ohtani, S. (1997). A community on snow algae on a Himalayan glacier: change of algal biomass and community structure with altitude. Arctic and Alpine Research, 29, 126-137.

Zawierucha, K., Buda, J., Pietryka, M., Richter, D., Łokas, E., Lehmann-Konera, S., Makowska, N. & Bogdziewicz, M. (2018). Snapshot of micro-animals and associated biotic and abiotic environmental variables on the edge of the south-west Greenland ice sheet. Limnology, 19, 141-150.

Zawierucha, K., Kolicka, M., Takeuchi, N. & Kaczmarek, Ł. (2015). What animals can live in cryoconite holes? A faunal review. Journal of Zoology, 295, 159-169.

Zawierucha, K., Ostrowska, M., Vonnahme, T.R., Devetter, M., Nawrot, A.P., Lehmann, S. & Kolicka, M. (2016a). Diversity and distribution of Tardigrada in Arctic cryoconite holes. Journal of Limnology, 75, 545-559.

Zawierucha, K., Vonnahme, T.R., Devetter, M., Kolicka, M., Ostrowska, M., Chmielewski, S., Kosicki, J.Z. (2016b) Area, depth and elevation of cryoconite holes in the Arctic do not influence Tardigrada densities. Polish Polar Research, 37, 325-334.

Zawierucha, K., Buda, J., Fontaneto, D., Ambrosini, R., Franzetti, A., Wierzgoń, M. & Bogdziewicz, M. (2019). Fine-scale spatial heterogeneity of invertebrates within cryoconite holes. Aquatic Ecology, 53, 179–190. https://doi.org/10.1007/s10452-019-09681-9

Figure captions

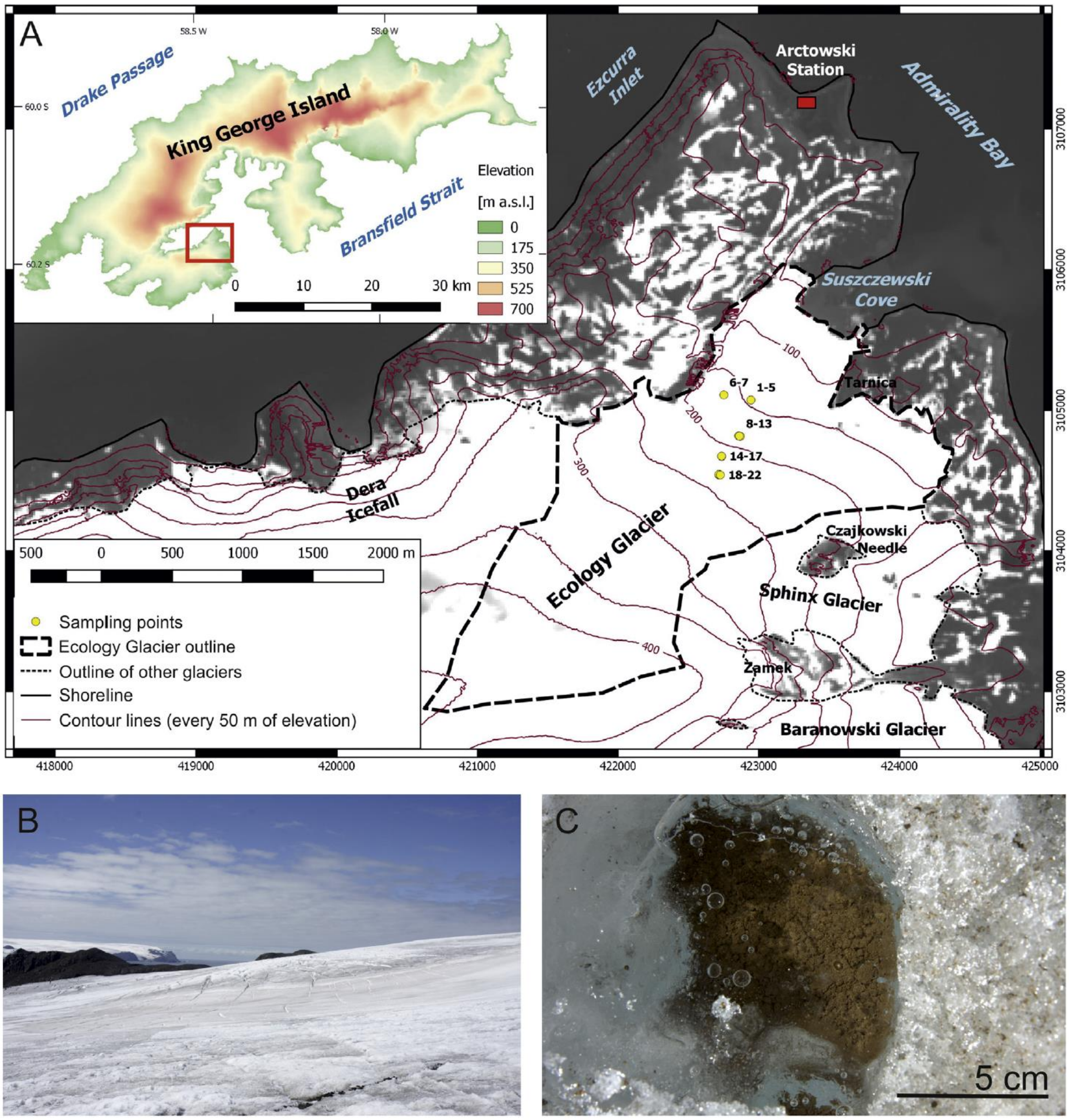

Figure 1. A: Map of study area, B: surface of Ecology Glacier in midsummer 2017, C: cryoconite hole on Ecology Glacier.

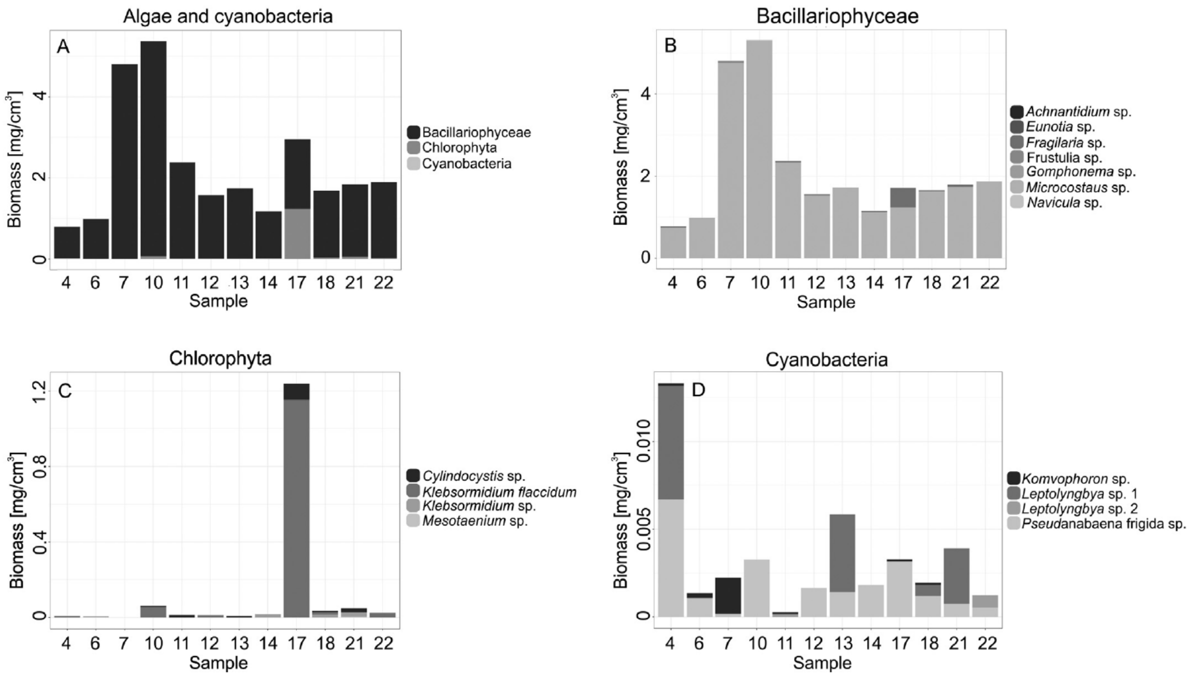

Figure 2. Biomass of cyanobacteria and algae in cryoconite holes from Ecology Glacier in mid Austral Summer 2017. A: Comparison of biomass between Bacillariophyceae, Chlorophyta and Cyanobacteria, B: Biomass of particular taxa among Bacillariophyceae, C: Biomass of particular taxa among Chlorophyta, D: Biomass of particular taxa among Cyanobacteria.

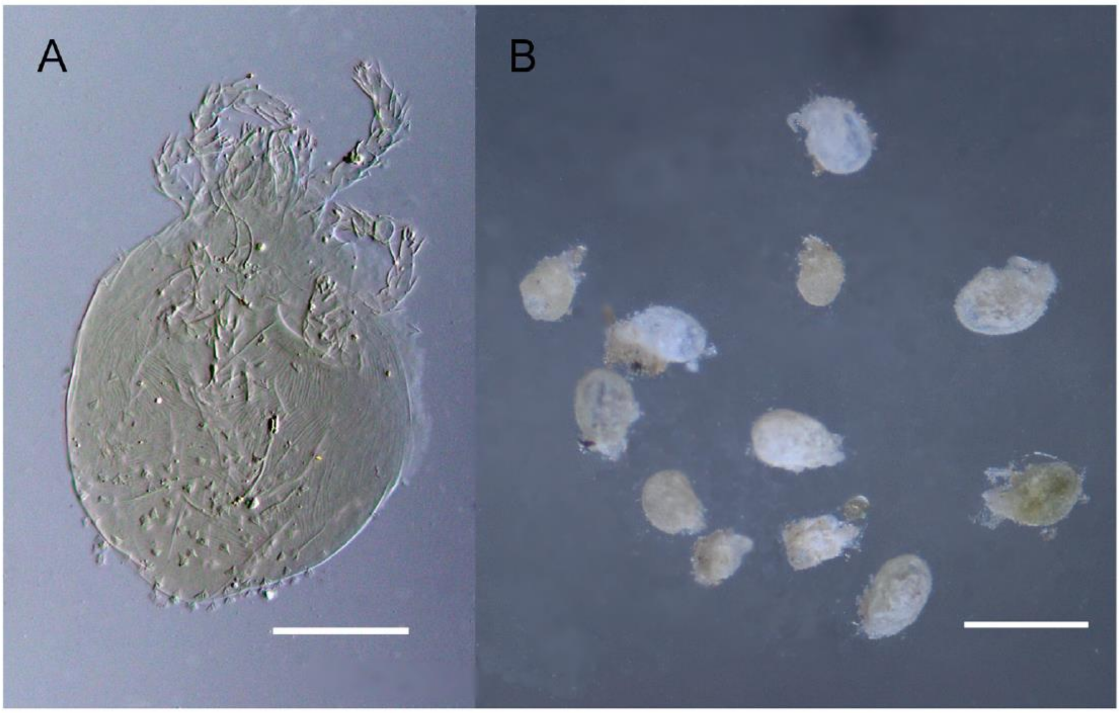

Figure 3. *Nanorchestes nivalis* (Trouessart, 1914) from cryoocnite holes: A- tritonymph mounted on slide (scalebar 100 µm), B- nymphs and few adults (scalebar 500 µm).

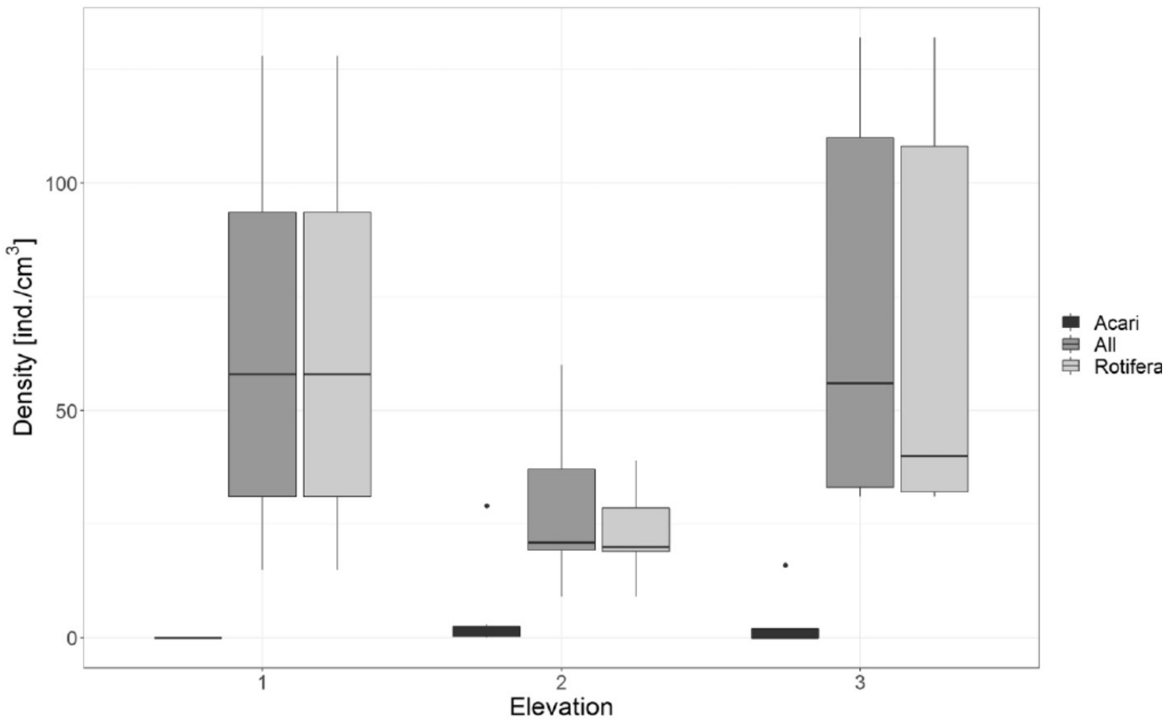

Figure 4. Densities of Acari, Rotifera and both in cryoconite holes from Ecology Glacier in mid Austral Summer 2017. Boxes denote 25th, 50th, and 75th percentiles; whiskers represent the lowest and highest datum within the 1.5 interquartile ranges of the lower and upper quartiles.

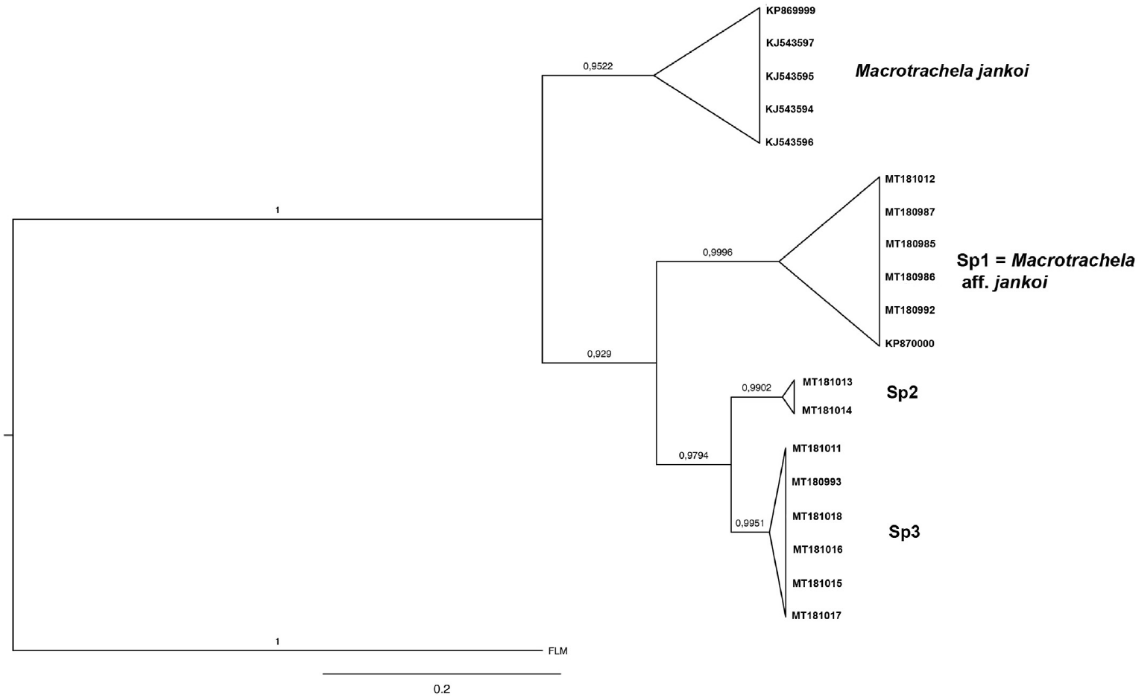

Figure 5. Species delimitation of rotifers found in cryoconite from Ecology Glacier (sp. 1, sp. 2, sp. 3), and their phylogenetic relationships to some Antarctic rotifer species (*Macrotrachela jankoi* s. str., *M.* aff. *jankoi*). Each clade represents a unique species (Independent Evolutionary Entity, IEE).

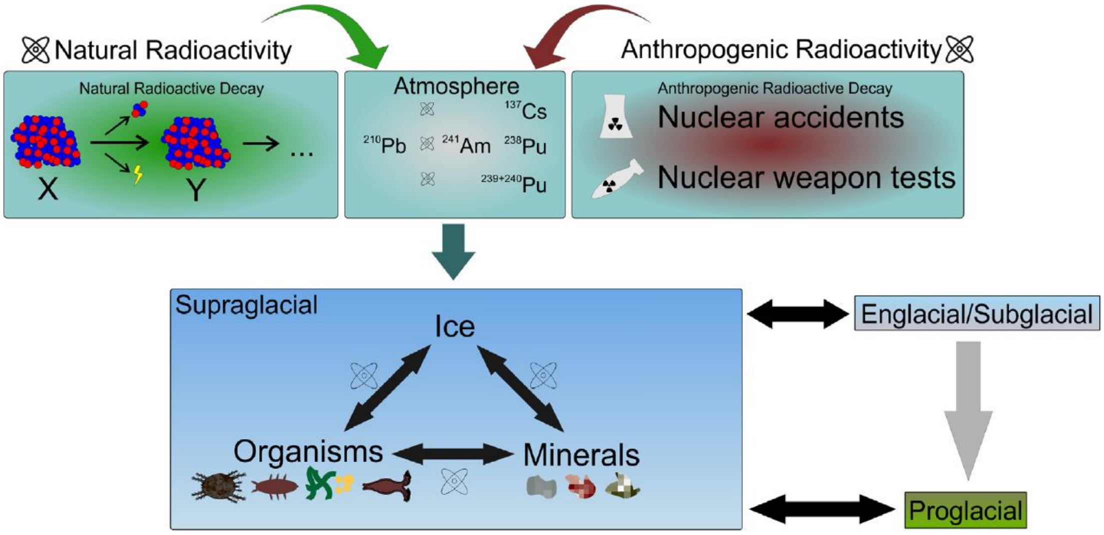

Figure 6. Scheme presents sources of radionuclides and their connections with ice, organisms and minerals.