



HAL
open science

Measurement report: Spatial variations in snowpack ionic chemistry and water stable isotopes across Svalbard

Elena Barbaro, Krystyna Koziol, Mats P Björkman, Carmen P Vega, Christian Zdanowicz, Jean-Charles Gallet, Daniel Kępski, Catherine Larose, Bartłomiej Luks, Florian Tolle, et al.

► To cite this version:

Elena Barbaro, Krystyna Koziol, Mats P Björkman, Carmen P Vega, Christian Zdanowicz, et al.. Measurement report: Spatial variations in snowpack ionic chemistry and water stable isotopes across Svalbard. *Atmospheric Chemistry and Physics*, 2021, 10.5194/acp-2020-740 . hal-03365920

HAL Id: hal-03365920

<https://hal.science/hal-03365920v1>

Submitted on 5 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



1 **Measurement report: Spatial variations in snowpack ionic chemistry and water stable**
2 **isotopes across Svalbard**

3

4 Elena Barbaro^{1,2}, Krystyna Koziol³, Mats P. Björkman⁴, Carmen P. Vega⁵, Christian Zdanowicz⁶, Tonu
5 Martma⁷, Jean-Charles Gallet⁸, Daniel Kępski⁹, Catherine Larose¹⁰, Bartłomiej Luks⁹, Florian Tolle¹¹,
6 Thomas V. Schuler^{12,13}, Aleksander Uszczyk¹⁴ and Andrea Spolaor^{1,2*}

7

8 ¹Institute of Polar Sciences, ISP-CNR, Via Torino 155, 30170 Venice Mestre, Italy

9 ²Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice,
10 Via Torino 155, 30172, Venice, Italy.

11 ³Department of Analytical Chemistry, Chemical Faculty, Gdansk University of Technology, G.
12 Narutowicza 11/12, 80-233 Gdańsk, Poland.

13 ⁴Department of Earth Sciences, University of Gothenburg, Box 460, SE-40530 Gothenburg, Sweden.

14 ⁵Dirección Meteorológica de Chile, Dirección General de Aeronáutica Civil, Portales 3450, Santiago,
15 Chile. *Previously at:* Department of Earth Sciences, Uppsala University, Villavägen 16, Uppsala,
16 Sweden.

17 ⁶Department of Earth Sciences, Uppsala University, Villavägen 16, SE-76236, Uppsala, Sweden.

18 ⁷Department of Geology, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn,
19 Estonia⁸Norwegian Polar Institute, Tromsø, No-9296, Norway

20 ⁹Institute of Geophysics, Polish Academy of Sciences, Księcia Janusza 64, 01-452 Warsaw, Poland

21 ¹⁰Environmental Microbial Genomics, Laboratoire Ampère, CNRS, University of Lyon, France

22 ¹¹Université de Franche-Comté, Besançon, FEMTO-ST, UMR 6174 CNRS

23 ¹²Department of Geosciences, University of Oslo, Oslo, Norway

24 ¹³Arctic Geophysics, University Center on Svalbard, UNIS, Longyearbyen, Svalbard, Norway

25 ¹⁴University of Silesia in Katowice, Faculty of Natural Sciences, Będzińska 60, 41-200 Sosnowiec,
26 Poland

27

28 ***Corresponding author**

29 Andrea Spolaor (andrea.spolaor@cnr.it)

30 **Keywords**

31 Snow, Svalbard, Arctic, inorganic ions, water isotopes

32

33

34

35



36 **Abstract**

37 The Svalbard archipelago, between 74° and 81° N, is ~60% covered by glaciers and located at the Arctic
38 sea ice edge. The region experiences rapid variations in atmospheric flow during the snow season (from
39 late September to May) and can be affected by air advected both from lower and higher latitudes, which
40 likely impact the chemical composition of snowfall. While long-term changes in Svalbard snow
41 chemistry have been documented in ice cores drilled from two high-elevation glaciers, the spatial
42 variability of the snowpack composition across Svalbard is comparatively poorly understood. Here, we
43 report the results of the most comprehensive seasonal snow chemistry survey to date, carried out in April
44 2016 across 22 sites on 7 glaciers across the archipelago. At each glacier, three snow pits were sampled
45 along altitudinal profiles and the collected samples were analysed for major ions (Ca^{2+} , K^+ , Na^+ , Mg^{2+} ,
46 NH_4^+ , SO_4^{2-} , Br^- , Cl^- and NO_3^-) and stable water isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$). The main aims were to investigate
47 the natural and anthropogenic processes influencing the snowpack and to better understand the influence
48 of atmospheric aerosol transport and deposition patterns on the snow chemical composition. The snow
49 deposited in the southern region of Svalbard was characterized by the highest total ionic loads, mainly
50 attributed to sea salt particles. Both NO_3^- and NH_4^+ in the seasonal snowpack reflected secondary aerosol
51 formation and post-depositional changes, resulting in very different spatial deposition patterns: NO_3^- had
52 its highest loading in northwestern Spitsbergen, and NH_4^+ in the southwest. The Br^- enrichment in snow
53 was highest in northeastern glacier sites closest to areas of extensive sea ice coverage. Spatial correlation
54 patterns between Na^+ and $\delta^{18}\text{O}$ suggest that the influence of long-range transport of aerosols on snow
55 chemistry is proportionally greater above 600-700 m a.s.l.

56

57 **1. Introduction**

58 Svalbard is a region of the Arctic experiencing rapid climate change, with a mean warming rate of +1.35
59 K per decade, much faster than the global average (Isaksen et al., 2016; Maturilli et al., 2013; Nordli et
60 al., 2014). This archipelago is located at the southern edge of the perennial Arctic sea ice, in the North
61 Atlantic Ocean, and is characterized by a maritime climate with large, rapid temperature variations
62 during winter (Brage et al., 2014). South-westerly inflow of mild oceanic air, associated with a low-
63 pressure system east of Iceland, often brings relatively warm and moist air in winter months, while Arctic
64 air intrusions from the north-east, driven by a high-pressure system over Greenland, result in much
65 colder temperatures (Rinke et al., 2017). In addition to these synoptic fluctuations, intense autumn or
66 winter cyclonic storms associated with anomalous warming events sometimes occur, transporting both
67 heat and moisture from lower latitudes to Svalbard (Rinke et al., 2017).

68

69 The aforementioned meteorological conditions also favor long-range transport of aerosols to the
70 archipelago, including pollutants from continental sources. Depending on the predominant air flow
71 pattern at the time of snowfall, the archipelago may experience regionally different amounts of both
72 snow accumulation (Eneroth et al., 2003; Forland et al., 2011) and chemical loads, the latter reflecting



73 contrasting mixtures of aerosol, varying by source area (Aas et al., 2016; Forsström et al., 2009; Möller
74 and Kohler, 2018). These regional differences are also associated with contrasts in sea ice cover. While
75 all Svalbard coasts are usually ice-free in summer, sea ice can form and cover large parts of the ocean
76 surface in the eastern and northern parts of the archipelago, while the southern and western parts often
77 remain ice-free (Dahlke et al., 2020), and therefore tend to experience greater snowfall owing to the
78 proximity of open water. In addition, the West Spitsbergen Current, a branch of the Atlantic Meridional
79 Overturning Circulation (AMOC) that flows to the west of the archipelago, causes markedly different
80 regional climatic conditions between its eastern and western parts (van Pelt et al., 2019): the west
81 exhibits higher temperatures and precipitation, while the east is less humid and cooler, and has also
82 experienced a stronger warming trend since 1957.

83

84 The seasonal snowpack contains a complex mixture of impurities that are either scavenged from the
85 atmosphere during snowfall or directly received through dry deposition (Kuhn, 2001). On land, the
86 majority of impurities found in seasonal snow are usually eluted during summer melting, influencing
87 terrestrial and aquatic systems (Björkman et al., 2014; Brimblecombe et al., 1987). However, in the
88 accumulation area of Arctic glaciers and ice caps, impurities can be retained within or below the seasonal
89 snow layer (Björkman et al., 2014; Pohjola et al., 2002; Vega et al., 2015b). For this reason, chemical
90 impurities such as major ions (Ca^{2+} , K^+ , Na^+ , Mg^{2+} , NH_4^+ , SO_4^{2-} , Br^- , Cl^- and NO_3^-) in ice cores have
91 been widely used to study past trends of atmospheric and climatic conditions (Barbante et al., 2017;
92 Isaksson et al., 2003; Thompson et al., 2002; Wolff et al., 2010). Previous studies in Svalbard (Goto-
93 Azuma et al., 1994; Nawrot et al., 2016; Semb et al., 1984; Winther et al., 2003) have shown that the
94 chemistry of the seasonal snowpack is dominated by sea salt ions (Hodgkins and Tranter, 2017).
95 However, the region is also a sink for atmospheric contaminants brought in by long-range transport
96 (Vecchiato et al., 2018). Investigations of precipitation and snow cover chemistry have predominantly
97 focused on the central and western parts of the archipelago (Kühnel et al., 2011; Nawrot et al., 2016;
98 Vega et al., 2015a; Virkkunen et al., 2007), due to the accessibility of research facilities in these sectors.

99

100 In the present study, the concentration, mass loading, spatial and altitudinal distribution of major ion
101 species (Ca^{2+} , K^+ , Na^+ , Mg^{2+} , NH_4^+ , SO_4^{2-} , Br^- , Cl^- and NO_3^-) in snow, together with its stable oxygen
102 and hydrogen isotope composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$), were evaluated in the late winter snowpack at 22
103 glacier sites across Svalbard. This study was part of the larger Community Coordinated Snow Study in
104 Svalbard (C2S3) project and the most comprehensive survey of seasonal snow chemistry in Svalbard to
105 date. The snowpack survey, which was carried out by coordinated teams using a standardized sampling
106 protocol (Gallet et al., 2018) aimed to map and characterize regional differences in the chemical
107 composition and impurity load of the winter snow pack, and interpret the observed differences in relation
108 to meteorological and other environmental factors. In this way, we aim to identify the conditions



109 controlling the chemistry of Svalbard snow that are susceptible to be influenced by future climate
110 warming across the region.

111

112 **2. Methods**

113 ***2.1 Sampling location and strategy***

114 During April 2016, the seasonal snowpack was sampled at 22 sites on seven glaciers across Svalbard:
115 Austfonna (AF) on Nordaustlandet, Lomonosovfonna (LF) on central Spitsbergen, Hansbreen (HB) and
116 Werenskiöldbreen (WB) in the Hornsund area of southern Spitsbergen, and Austre Lovénbreen (ALB),
117 Kongsvegen (KVG) and Holtedahlfonna (HDF) in the vicinity of Ny-Ålesund on northwestern
118 Spitsbergen (Table 1 and Figure 1). The glaciers are of different sizes and hypsometries. Each glacier
119 was sampled in the ablation zone, close to the equilibrium line altitude (ELA), and in the accumulation
120 zone (Table 1). The ELA is the elevation at which the surface mass balance is zero, i.e., where the
121 accumulation of snow is exactly balanced by ablation over a period of a year (Cogley et al., 2011).
122 Although the exact elevation range of these zones differ for each glacier, they share enough glaciological
123 similarities to support inter-site comparisons. Snowpit sampling was performed using a standardized
124 common protocol (Gallet et al., 2018) with pre-cleaned equipment (i.e., tubes, plastic scrapers and plastic
125 shovels cleaned with ultrapure water) and protective clothing (powder-free plastic gloves, clean suits and
126 face masks). Samples for ionic chemistry were taken in each discrete snow pit layer, according to the
127 visible stratigraphy, and directly into pre-cleaned, 50 mL polypropylene "Falcon" centrifuge tubes.
128 Samples for the isotopic composition of water were collected at a 5-cm resolution for sites in the Ny-
129 Ålesund area and at a 10-cm or stratigraphic layer resolution for other sites. All sampling was conducted
130 in a safe distance and upwind from potential local pollution sources, such as the snowmobiles used as
131 transport by the sampling team.

132

133 ***2.2 Major ion analyses***

134 Samples from glaciers in the Hornsund region (HB, WB) were analysed at the Polish Polar Station
135 Hornsund (Institute of Geophysics, Polish Academy of Sciences), while samples from glaciers near Ny-
136 Ålesund (KVG, ALB, HDF) were shipped frozen to the Institute of Polar Sciences (ISP-CNR) in Venice
137 (Italy). Snow sampled in central Spitsbergen (AF, LF) was shipped frozen to the Department of Earth
138 Sciences at Uppsala University (Sweden). Due to a temporary equipment malfunction in Uppsala, only
139 cations could be analysed there, and the refrozen samples were forwarded to ISP-CNR for anion analysis.
140 All samples and standards were handled and prepared under clean room conditions, wearing powder-free
141 gloves. In all labs except at the Polish Polar Station Hornsund, laminar flow hoods (class 100) were used.
142 Samples were melted immediately before analysis.

143

144 ***2.2.1. Hornsund***



145 Samples were filtered through 0.45 μm mixed cellulose esters membranes (Merck Millipore S-pak®)
146 prior to analysis. Ion concentrations were determined on a Metrohm 761 Compact IC ion chromatograph
147 equipped with an autosampler (Metrohm, Herisau, Switzerland), with isocratic flow, and chemical
148 suppression for anions (column Metrosep A Supp S + Metrosep A Supp 4/5 Guard 4.0, eluent: NaHCO_3
149 1.0 mmol L^{-1} + Na_2CO_3 3.2 mmol L^{-1}). Cations were determined without suppression (column Metrosep
150 C4 + Metrosep C4 Guard; eluent: HNO_3 1.7 mmol L^{-1} + 2,6-pyridinecarboxylic acid [dipicolinic acid, or
151 DPA] 0.7 mmol L^{-1}). Cation samples were acidified with 2 μL of 2mM HNO_3 per 10 mL sample prior to
152 analysis, as recommended for this device and column. The injection volume was 20 μL in the anion
153 system and 100 μL in the cation system. Nitric acid solutions were prepared from POCH S.A. (Poland)
154 concentrated weighed amounts, while sodium carbonate and hydrogen carbonate, as well as DPA, were
155 dissolved from solid phase (Merck Millipore).

156

157 2.2.2 Uppsala

158 Samples were filtered using 0.22 μm polyethersulfone membranes (Minisart®, Sartorius) and anion
159 determinations were performed using a Metrohm ProfIC850 ion chromatograph (Metrohm, Herisau,
160 Switzerland), equipped with an autosampler and a Metrosep C4 column. The mobile phase of 0.02 M
161 DPA and 0.1 M HNO_3 was run in isocratic flow of 0.7 mL min^{-1} . Very low detection limits ($\leq 0.006 \text{ mg L}^{-1}$)
162 were achieved thanks to the sample injection volume of 500 μL .

163

164 2.2.3. Venice

165 Anion determination was performed using a Dionex™ ICS-5000 ion chromatograph
166 (ThermoScientific™, Waltham, US) equipped with an anionic exchange column (Dionex IonPac AS 11,
167 $2 \times 250 \text{ mm}$) and a guard column (Dionex IonPac AG11 $2 \times 50 \text{ mm}$). Sodium hydroxide (NaOH), used
168 as a mobile phase, was produced by an eluent generator (Dionex ICS 5000EG, Thermo Scientific). The
169 injection volume was 100 μL . The IC was coupled to a single quadrupole mass spectrometer (MSQ
170 Plus™, Thermo Scientific™) with an electrospray source (ESI) that operated in negative mode. To
171 determine cations, a capillary ion chromatograph (Thermo Scientific Dionex ICS-5000), equipped with a
172 capillary cation exchange column (Dionex IonPac CS19-4 μm , $0.4 \times 250 \text{ mm}$) and a guard column
173 (Dionex IonPac CG19-4 μm , $0.4 \times 50 \text{ mm}$), was used, coupled to a conductivity detector. The injection
174 volume was 0.4 μL . All details about the anion and cation methods are reported by (Barbaro et al., 2017).

175

176 2.2.4. Instrumental performance of each laboratory

177 For all laboratories, calibration for ions were evaluated using analytical standards (Merck/Sigma
178 Aldrich). The calibrations in each lab gave different linear ranges for each ion due to the different
179 methods used (Table S1). Good linearity was demonstrated in each lab and all calibration curves had
180 $R^2 > 0.99$. Samples that had ion concentrations beyond the calibration range were diluted with ultrapure
181 water before re-analysis. Analytical blanks of ultrapure water ($>18 \text{ M}\Omega\cdot\text{cm}$) were included in the



182 analysis at all three labs. The method detection limit (MDL) was set to three times the standard deviation
183 of the blank values (Table S1). For Na^+ , Mg^{2+} , Cl^- and SO_4^{2-} , values $<\text{MDL}$ occurred in less than 10% of
184 cases, and for Ca^{2+} and NO_3^- the $<\text{MDL}$ concentrations were noted in 12% and 17% of cases,
185 respectively. However, K^+ and Br^- were detected only in 53% and 46% of all samples, respectively,
186 while NH_4^+ concentration exceeded the MDL only in 36% of all measurements. For the calculation of
187 bulk ionic loading in snow pits, values $<\text{MDL}$ were assumed to be equal to half the MDL.

188

189 Accuracy and precision are important parameters to evaluate during method validation. Checks for
190 accuracy were made using certified multi-element standard solutions for anions (F^- , Cl^- , Br^- , NO_3^- , SO_4^{2-} ,
191 n° 89886-50ML-F, Sigma Aldrich) and cations (Na^+ , K^+ , Mg^{2+} , Ca^{2+} , n° 89316-50ML-F, Sigma Aldrich),
192 at the concentration of $10 \text{ mg L}^{-1} \pm 0.2\%$. Accuracy is expressed as a relative error calculated as
193 $(Q-T)/T \times 100$, where Q is the determined value and T is the “true” value. The accuracy for each ion in all
194 labs was always $<\pm 10\%$, except for Mg^{2+} measurements at the Hornsund laboratory. The analytical
195 precision was quantified as the relative standard deviation (RSD) for replicates ($n > 3$) of standard
196 solutions and was always $< 10\%$ for each ion (Table S1).

197

198 **2.3. Stable water isotopes**

199 The determination of stable isotope ratios of O and H was performed at Tallinn University of Technology
200 using a Picarro L2120-i water isotope analyser with a high-precision AO211 vaporizer. Results are
201 reported in the standard delta notation as $\delta^{18}\text{O}$ and $\delta^2\text{H}$ relative to VSMOW. Reproducibility was $\pm 0.1\%$
202 for $\delta^{18}\text{O}$ and $\pm 1\%$ for $\delta^2\text{H}$, respectively.

203



204 3. Results

205 3.1 Spatial distribution of ionic species

206 To investigate differences in snowpack composition across all glaciers, we compared the total mass of
207 ions that accumulated in snow at the different sampling sites. On average, the snow cover season on
208 Svalbard lasts from early September to early May, but snow may also fall in summer months at high
209 elevations. The snow pits in this study were sampled in early to late April 2016 and might therefore not
210 contain the full annual ionic burden, since deposition might occur also in other months. Therefore, we
211 report these data as ionic loads (mg m^{-2}) rather than annual fluxes. In each snow pit, the ionic load was
212 calculated as the cumulative sum of the ionic concentrations multiplied by the snow water equivalent in
213 each discrete layer. The snowpack chemical characteristics were then compared between glacier zones
214 (ablation zone, ELA, and accumulation zone; Table 2, Figure 1).

215

216 Snow pits samples collected in the Hornsund area (southern Spitsbergen) showed a markedly higher total
217 load for all major ions (Figures 1 and 2) than at all other sites. The samples collected in the accumulation
218 zones of WB and HB had total ionic loads of 8161 and 8023 mg m^{-2} , respectively, four times higher than
219 those collected in the same zone at KVG (2861 mg m^{-2}), AF (2607 mg m^{-2}) and ALB (1934 mg m^{-2}) and
220 16 times higher than those sampled at LF (639 mg m^{-2}) and HDF (583 mg m^{-2}). Similar differences were
221 observed for the snow pits collected at lower altitudes (Figure 2).

222

223 In the accumulation zone of all glaciers (Figure S1), Na^+ and Cl^- were generally the most abundant ionic
224 species, with percentages ranging from 29% (HDF) to 36% (AF) for Na^+ , and from 34% (LF) to 48%
225 (HB and WB) for Cl^- , respectively. The snowpack on Hornsund glaciers (HB, WB) had higher Cl^-
226 percentages (48-49%) compared to that of other glaciers (34-39%), while conversely the SO_4^{2-} percentage
227 was lower there (9%) than on other glaciers (11-23%). The ionic loads were generally highest in the
228 accumulation zone of glaciers, and lowest in the ablation zone (Figure 2), mostly due to the lower snow
229 accumulation and greater wind deflation at lower elevations. This pattern held true for Na^+ , Cl^- , NH_4^+ ,
230 K^+ , Ca^{2+} , and Mg^{2+} at most glacier sites, except in the Hornsund region. The load of Br^- was similar on
231 glaciers of the Ny-Ålesund sector (ALB, HDF, KVG) and on LF, but was higher in AF and Hornsund
232 glaciers (HB, WB; Figure 2). The load of NO_3^- was similar for all glaciers, except for LF, where very low
233 loads were found. Unlike total SO_4^{2-} , the non-sea-salt fraction of sulphate (nss-SO_4^{2-}), calculated using a
234 seawater $\text{SO}_4^{2-}:\text{Na}^+$ mass ratio of 0.252, (Millero et al., 2008) showed lower loads on Hornsund glaciers
235 (15-107 mg m^{-2}) when compared to glaciers in other parts of the archipelago (Figure 1, Table 2). The
236 nss-SO_4^{2-} loads varied between 22-131 mg m^{-2} at HDF and LF, 75-266 mg m^{-2} at KVG and ALB, and
237 153-206 mg m^{-2} at AF.

238

239 3.2 Stable water isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$)



240 Our results provide the first picture of spatial variations in the mean stable water isotope composition of
241 the seasonal snowpack across Svalbard (Table 2, Figure S2). The snow water equivalent (SWE)-
242 weighted mean $\delta^{18}\text{O}$ and $\delta^2\text{H}$ decreased significantly from south to north (Spearman rank correlation p
243 with latitude was -0.69 and -0.65 for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, with $p < 0.001$ and $p < 0.01$, respectively). The
244 isotopically heaviest snow (least negative δ values) occurred on glaciers of the Hornsund region ($\delta^{18}\text{O}$: $-$
245 11.25 to -9.54 ‰; $\delta^2\text{H}$: -77.62 to -63.64 ‰), and the isotopically lightest (most negative δ values) in AF
246 ($\delta^{18}\text{O}$: -16.00 to -13.89 ‰; $\delta^2\text{H}$: -111.15 to -96.89 ‰). Glacier sites in NW Spitsbergen and on LF had
247 mean $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values that fell within these ranges. On KVG, ALB, HDF and LF, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$
248 in snow decreased monotonically (becoming gradually more negative) with increasing elevation.
249 However, on other glaciers this pattern did not hold: on AF, we found an increase from AF1 to AF2, but
250 a decrease from AF2 to AF3; on WB the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ were similar at WB1 and WB2, but less negative
251 at WB3. On HB there was no statistical difference between the mean $\delta^{18}\text{O}$ and $\delta^2\text{H}$ value in all snow pits.
252 A general, significant anticorrelation with altitude was found for SWE-weighted mean $\delta^2\text{H}$ ($\rho = -0.63$,
253 $p < 0.01$), and $\delta^{18}\text{O}$ ($\rho = -0.65$, $p < 0.01$).

254

255 4. Discussion

256

257 There have been few published studies on recent seasonal snow or firn chemistry in Svalbard, hence
258 comparisons of our data with these earlier results are limited to a few sites. (Virkkunen et al., 2007) and
259 (Vega et al., 2015a) and unpublished data) quantified the annual chemical loads of Na^+ , Ca^{2+} , NO_3^- and
260 nss-SO_4^{2-} at Lomonosovfonna summit (LF3) from 2002 to 2011 using snow and firn cores, and our study
261 extends these data to 2016. The range of annual ionic loads at LF3 over the 15-year period is remarkably
262 wide, but no clear temporal trend can be identified (Table 3). At Holtedahlfonna summit (HDF3), firn
263 core measurements by (Spolaor et al., 2013) found a mean Na^+ concentration of $110 \pm 73 \text{ ng g}^{-1}$ over the
264 period 2003-2012, while the mean concentration in the April 2016 snowpack (this study) was 191 ng g^{-1} ,
265 hence within the range reported in earlier years.

266

267 4.1 The main ion sources in the Svalbard seasonal snow

268 The composition of the Svalbard seasonal snowpack sampled during the C2S3 project clearly indicates
269 that the ocean is the main source of ions in snow, as was shown by Hodgkins and Tranter (2017). At all
270 sites, the dominant ions are Na^+ , Cl^- , and SO_4^{2-} , with comparatively minor amounts of K^+ , Ca^{2+} and Mg^{2+}
271 (Figure S1). To help clarify the possible sources and modes of deposition of ions in snow, we computed
272 Spearman rank correlations between total ionic loads (ρ_{load}), as well as between volume-weighted mean
273 ionic concentrations (ρ_{conc}), across all snow pits ($n = 22$; Table 4). The chemical species that are
274 predominantly wet-deposited and sharing common sources and not undergoing significant composition
275 changes in transport should exhibit similar concentration patterns (high ρ_{conc}) (Schüpbach et al., 2018).
276 The concentrations of Mg^{2+} , K^+ and Ca^{2+} were all positively correlated with those of Na^+ and Cl^- ,



277 indicating a common sea spray source. The ρ_{load} correlations are very similar for these ionic species,
278 which points to both wet and dry deposition being a significant mechanism in their accumulation in
279 snowpack.

280

281 The concentrations of Mg^{2+} were positively and significantly correlated with both Ca^{2+} and nss-Ca^{2+} (ρ_{conc}
282 = 0.70 and 0.47, respectively; the latter coefficient was higher for loads at 0.56; Table 4), suggesting they
283 share some non-marine source(s). Furthermore, all glaciers had greater $\text{Ca}^{2+}:\text{Mg}^{2+}$ ratios than seawater
284 (0.32; (Millero et al., 2008) (Figure 3). It is likely that the excess Ca^{2+} and Mg^{2+} came from mineral
285 particles, i.e. CaCO_3 (calcite), and local rock (or soil) dust (Kekonen et al., 2005) derived from calcareous
286 rocks, especially limestone, dolostone and marble, which are abundant in (Dallmann, 1999) The presence
287 of carbonate ions in the collected snow samples would explain the missing negative charge in the ionic
288 balance (anion X^- ; Figure S3).

289

290 Sulphate (SO_4^{2-}) was highly and significantly (p -value < 0.05) correlated with both Na^+ ($\rho_{\text{load}} = 0.92$; ρ_{conc}
291 = 0.80) and Cl^- ($\rho_{\text{load}} = 0.93$; $\rho_{\text{conc}} = 0.75$), indicating that sea spray is its main source. However $\text{Na}^+/\text{SO}_4^{2-}$
292 and $\text{Cl}^-:\text{SO}_4^{2-}$ ratios were well below seawater values (Millero et al., 2008) on most glaciers except those
293 near Hornsund (WB and HB), suggesting inputs of nss-SO_4^{2-} (Figure 3). Biogenic nss-SO_4^{2-} can be
294 deposited in the snow as an oxidized by-product of dimethyl sulphide (DMS) emitted by marine algal
295 blooms (Gondwe et al., 2003), typically initiated in April but sometimes later (Ardyna et al., 2013).
296 Another plausible source of nss-SO_4^{2-} deposition in Svalbard is long-range transport of SO_4^{2-} aerosols
297 from biomass burning in the spring, or from fossil fuel combustion throughout the winter (Barrie, 1986;
298 Law and Stohl, 2007; Nawrot et al., 2016). The nss-SO_4^{2-} did not correlate significantly with other ionic
299 species, suggesting a separate origin. An extra consideration is that in the southern region of the
300 archipelago, the higher sea spray input could partially mask the nss-SO_4^{2-} signal, which is a derived
301 variable, because the larger uncertainty for greater Na^+ concentrations would disproportionately affect
302 estimations of nss-SO_4^{2-} at these sites.

303

304 Bulk ionic loads of SO_4^{2-} in the snow pits were significantly and positively correlated with those of NO_3^-
305 ($\rho_{\text{load}} = 0.55$) and NH_4^+ ($\rho_{\text{load}} = 0.68$), but the correlations between weighted mean ionic concentrations
306 were not significant, hinting at co-deposition (wet) rather than shared sources (Table 4). These species
307 are known to form secondary aerosols (Karl et al., 2019; Schaap et al., 2004) and thus their proportions
308 in aerosols may differ significantly from those in their source emissions. It is also possible that nitrogen
309 species underwent further post-depositional photochemical reduction and evasion, thereby reducing their
310 concentrations in snow (Curtis et al., 2018). Finally, we remark here that the snow pit sampling was done
311 in April, earlier than the beginning of the oceanic algal bloom in the surrounding Svalbard basin, which
312 could have led to underrepresentation of biological emissions from late spring in our samples.

313



314 Spatial variations of ammonium loads (NH_4^+) across Svalbard glaciers mirrored the pattern shown by sea
315 salt ions, with higher loads in the Hornsund region and lower loads in other areas. This was also reflected
316 by significant correlations between bulk loads of NH_4^+ with those of Na^+ and Cl^- ($\rho_{\text{load}} = 0.64$ and 0.73 ,
317 respectively), and with Na^+ , K^+ and Mg^{2+} by concentration ($\rho_{\text{conc}} = 0.47$, 0.62 and 0.47 , respectively), the
318 latter relationships suggesting that some ammonium is deposited as coatings on crustal aerosols
319 (Eastwood et al., 2009). Ammonium has been linked to biogenic, forest fire, and anthropogenic
320 agricultural emissions (Trachsel et al., 2019). The higher annual snowpack load of NH_4^+ , determined in
321 the Hornsund region is more likely connected with biological sources than anthropogenic activities,
322 although some contribution from biomass burning events cannot be excluded. The marine primary
323 productivity in spring 2016 (April and May) was higher in the south-eastern ocean sector of the Svalbard
324 archipelago (Figure S4), which could partially explain the higher NH_4^+ load. This would also explain the
325 correlation between ammonium and sea-salt ions (Table 4). Locally, especially for HB, there may be
326 extra NH_4^+ emissions from bird colonies (Keslinka et al., 2019; Wojczulanis K. et al., 2008).

327

328 Unlike NH_4^+ , the bulk loading of NO_3^- in snow was highest in northwestern Spitsbergen (Ny-Ålesund
329 area), when compared to other parts of Svalbard. Deposition of NO_3^- in Arctic snow is often associated
330 with the long-range atmospheric transport of NO_x and related N species from anthropogenic source
331 regions at lower latitudes (Björkman et al., 2014; Fibiger et al., 2016; Vega et al., 2015a). Differences in
332 NO_3^- loads in snow in various parts of Svalbard might therefore reflect differences in the transport
333 pathways of precipitating air masses, including formation of secondary aerosols, or post-depositional
334 processes, rather than local emissions. While local shipping routes and the settlement of Ny Ålesund
335 itself may contribute NO_3^- emissions (Winther et al., 2014), the highest share of the total ionic load of
336 NO_3^- was found in the accumulation zone of HDF (9% of the total ionic load; Figure S1). Given that
337 HDF is the most remote site from Ny Ålesund relative to KVG or ALB, it should not capture a high
338 share of local pollution. The highest correlation coefficient for NO_3^- , both in terms of concentrations and
339 loads, was found with nss-Ca^{2+} . This would support both the formation of calcium nitrate in the
340 atmosphere (Gibson et al., 2006) or post-depositional processes removing the NO_3^- from layers poor in
341 Ca^{2+} , since calcium has been hypothesised to stabilise the nitrate in snowpack against post-depositional
342 losses (Kekonen et al., 2017).

343

344 4.2. Chlorine depletion

345 Although Na^+ and Cl^- , the main species of sea salt, were significantly correlated ($\rho_{\text{conc}} = 0.95$), the values
346 of the Cl^-/Na^+ ratio in snow were lower than that in seawater on most studied glaciers, except those near
347 Hornsund (Figure 3), suggesting a Cl^- deficit at the more northerly sites. A possible explanation of this
348 Cl^- deficit might be de-chlorination of the sea spray aerosol during transport or, less likely, at the snow-
349 atmosphere interface. This reaction occurs between sea salt particles, containing NaCl , and NO_3^- , SO_4^{2-} ,
350 or organic acids to release gaseous HCl (Zhuang et al., 1999). We calculated the percentage of Cl^-



351 depletion (Cl_{dep}^-) as $Cl_{dep}^- = (Cl_{ss}^- - Cl_{meas}^-) / Cl_{ss}^- \times 100\%$, where $Cl_{ss}^- = 1.174 Na_{meas}^+$, and Cl_{meas}^- and
352 Na_{meas}^+ are the measured equivalent concentrations (Yao et al., 2003). Except for site HDF2 ($Cl_{dep}^- = 2\%$),
353 the lowest mean Cl_{dep}^- values were obtained for Hornsund glaciers (WB, HB: 10–19%), while values at
354 other glacier sites ranged between 21 and 75% (Table 2). This suggests that sea-salt aerosols travel along
355 a route from southern to northern Svalbard, which gives more time for Cl^- depletion in the ionic mixtures
356 reaching more northerly locations.

357

358 **4.3. Bromine enrichment**

359 In addition to Cl^- , snowfall can scavenge Br^- (Peterson et al., 2019; Spolaor et al., 2019), and Br^- loads on
360 Svalbard glaciers surveyed in April 2016 were positively and significantly correlated with those of
361 primary sea salt ions Na^+ ($\rho_{load} = 0.48$), Cl^- ($\rho_{load} = 0.53$) and Mg^{2+} ($\rho_{load} = 0.51$) (Table 4). Correlations
362 between weighted mean concentrations were not significant, however, suggesting departures of the Br^-
363 concentrations in snow from typical seawater ionic ratios at some glacier sites. A Br^- enrichment factor
364 (Br_{enr}) can be calculated as $Br_{enr} = Br^- / (0.0065 Na^+)$, where 0.0065 is the $Br^- : Na^+$ seawater mass ratio
365 (Maffezzoli et al., 2017). The Br_{enr} reflects specific processes (in particular sea ice Br^- emission) that
366 affect the Br^- concentration and load in the snowpack (Spolaor et al., 2014). Results of our calculations
367 (Table 2, Figure S5) show that on glaciers of the Hornsund area (HB and WB) and NW Spitsbergen
368 (KVG, ALB and HDF), the mean Br_{enr} values are often, but not always, < 1 , indicating some Br^-
369 depletion, in agreement with the findings of (Jacobi et al., 2019) for glaciers in the Ny Ålesund area. The
370 depletion could be a result of snowpack Br^- re-emission, but this seems unlikely since field measurements
371 near Ny-Ålesund found no evidence of such volatilization of snow-bound Br^- (Spolaor et al., 2019).

372

373 Alternatively, Br^- depletion could occur through BrO loss from marine aerosols and subsequent
374 deposition of these Br^- -depleted aerosols in snow. In contrast to southern and northwestern Spitsbergen,
375 glaciers in central Spitsbergen (LF) and in Nordaustlandet (AF), showed Br_{enr} values > 1 . These glaciers
376 lie relatively close to areas to the east of the archipelago that are often covered by first-year sea ice.
377 Newly-formed sea ice has been shown to release gas phase Br^- into the polar atmosphere, thus supplying
378 an extra Br^- source in addition to sea spray (Spolaor et al., 2016). The spatial distribution of the Br^-
379 enriched snow pit sites supports this : sites closest to areas covered by first-year sea ice have the largest
380 Br^- enrichments, and the latter decrease with greater distance from the eastern shores of Svalbard (Figure
381 S5). A survey of the average sea ice coverage in the period March-May 2016, which is relevant to the Br^-
382 enrichment phenomenon (data by Norwegian Meteorological Institute) confirms that the north-eastern
383 and eastern shore of Svalbard were indeed covered much more frequently by close and open drift ice
384 than the south or north-west.

385

386 **4.4 Distribution pattern of $\delta^{18}O$ and δ^2H**



387 As described earlier, the SWE-weighted mean $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in glacier snow pits decreased
388 significantly with increasing latitude across Svalbard, the least negative values occurring on glaciers of
389 the Hornsund region, and the most negative in Austfonna (Table 2). This pattern follows the climate
390 gradient across the archipelago, milder in the south, colder in the north. Part of the south-north contrast in
391 δ values could be explained by the lower mean altitude of glacier sites in the Hornsund region compared
392 to some of the higher-elevation sites further north on Spitsbergen or on Austfonna, and the relationship
393 with elevation was similar for both isotopic ratios in the collected dataset.

394 The deuterium excess ($d = \delta^2\text{H} - (8 \cdot \delta^{18}\text{O})$) is mainly influenced by the source region of the precipitating
395 moisture and in particular by the sea surface temperature. In addition, d is also influenced by the
396 temperature gradient between the moisture source and precipitation area. The SWE-weighted mean d
397 values in Svalbard snow pits varied within a relatively narrow range of 6.74‰ (from 10.10 to 16.84 ‰),
398 and similarly to $\delta^{18}\text{O}$, showed no clear gradient with elevation or longitude. Deuterium excess showed a
399 significant correlation with latitude, at $p = 0.60$ ($p < 0.01$). A more detailed analysis of d by latitude
400 showed that only beyond 79.2 °N, i.e. in Austfonna snow pits, was d significantly different than at other
401 sites (Kruskal-Wallis test, $z = 4.23$, $p < 0.04$). This is consistent with lower temperatures and evaporation
402 rates in the more northern waters around Svalbard, and suggests that snowfall on AF is at least partly
403 affected by a different, more northerly moisture source than the rest of the archipelago.

404

405 **4.5 Effect of elevation: a case study of Na**

406 The glacier survey carried out during the C2S3 project afforded the opportunity to investigate the
407 possible effect of elevation on the ionic composition of the snowpack. To do this, we compared the bulk
408 load and SWE-weighted mean concentration of Na^+ across all studied snow pits, ordered by elevation
409 (Figure 4). Overall, both Na^+ loads and concentrations decreased with increasing altitude ($\rho_{\text{load}} = -0.24$,
410 $p > 0.05$; $\rho_{\text{conc}} = -0.72$, $p < 0.05$). This likely reflects greater local sea spray aerosol deposition at lower,
411 compared to higher, glacier sites. We then computed linear (Pearson) correlation coefficients (R , with
412 associated p -values) between log-transformed Na^+ loadings ($\log(\text{Na}_{\text{load}})$) and $\delta^{18}\text{O}$ for all snow pits in the
413 accumulation zones of glaciers (Figure 5). The calculation was performed with all snow layers. The Na^+
414 load was used as sea-spray tracer, while the $\delta^{18}\text{O}$ was assumed to vary with moisture source between
415 discrete snowfall events. We found that the positive correlation between $\log(\text{Na}_{\text{load}})$ and $\delta^{18}\text{O}$ increased
416 with elevation from $R = 0.1$ (HB3; 396 m a.s.l.) to $R = 0.65$ (LF3; 1193 m a.s.l.), and reached a 95 %
417 threshold of significance ($R > 0.3$) for glaciers sites above 600 m a.s.l. (KVG, AF, LF and HDF; Figure
418 5). The average distance was a comparatively negligible factor in explaining the correlation between
419 $\log(\text{Na}_{\text{load}})$ and $\delta^{18}\text{O}$.

420

421 The increase in strength and significance of the $\log(\text{Na}_{\text{load}})$ - $\delta^{18}\text{O}$ correlation with altitude might be
422 explained by different contributions of locally-emitted ssNa^+ , relative to those of Na^+ from more distant
423 sources. Sites located at lower altitudes are proportionally more affected by local sea spray deposition,



424 with or without snowfall. Conversely, sites at higher elevations likely receive a larger share of their ionic
425 load from more distant sources, and by wet deposition through snowfall. At the four sites (KVG, AF, LF
426 and HDF) where the $\log(\text{Na}_{\text{load}})$ - $\delta^{18}\text{O}$ correlation was significant, increases in $\delta^{18}\text{O}$ in snow layers were
427 often associated with higher Na^+ concentrations. The isotopically heavier (less negative) $\delta^{18}\text{O}$ values
428 suggests that the co-registered Na^+ enhancements were associated with precipitation of relatively warm
429 air, probably advected from lower latitudes. Air masses arriving from the south travel across the ocean
430 for an extended time, which can enrich them in sea spray aerosol and hence in Na^+ . It is also possible that
431 the poorer $\log(\text{Na}_{\text{load}})$ - $\delta^{18}\text{O}$ correlation at lower altitude glacier sites is partly due to stronger post-
432 depositional modification of isotopic and ionic signals in snowpack related to more frequent melt-
433 refreeze episodes.

434

435 **5. Summary and Conclusion**

436 We have quantified and described, for the first time, the spatial distribution of major ion loads (Ca^{2+} , K^+ ,
437 Na^{2+} , Mg^{2+} , NH_4^+ , SO_4^{2-} , Br^- , Cl^- and NO_3^-) and variations of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in the snowpack on glaciers
438 across Svalbard for a single accumulation season (2015-2016). The highest total ionic loads were found
439 in the southern region of Spitsbergen (Hornsund area), and exceeded 8 g m^{-2} . Conversely, the lowest total
440 ionic loads ($\leq 0.6 \text{ g m}^{-2}$) were found at sites in central or northwestern Spitsbergen (LF and HDF). Sea
441 salt ions (Cl^- , Na^+ and SO_4^{2-}) dominated the ionic loads at all sites, but their share was highest at sites
442 near Hornsund, for e.g., 48% Cl^- , compared to only 29% on Holtedahlfonna. Relatively elevated
443 $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratios in snow at all sites indicated non-sea-salt Ca^{2+} inputs, most likely in the form of
444 carbonate dust. Unlike other ions, NO_3^- had the highest loads in glaciers of northwestern Spitsbergen, and
445 the lowest at LF. The nitrogen species, NO_3^- and NH_4^+ , showed distinct spatial distribution patterns. The
446 highest NO_3^- loads were found in the northwestern part of Svalbard, while the highest NH_4^+ loads were in
447 the southwest. Bromide (Br^-) was most enriched in snow relative to seawater at AF and LF, the glacier
448 sites located closest to areas with first-year sea ice cover. This supports first-year sea ice being an
449 important source of non-sea salt Br^- in the polar atmosphere.

450

451 An increasing, positive correlation between $\log(\text{Na}_{\text{load}})$ and $\delta^{18}\text{O}$ as a function of elevation sites suggests
452 that locations above 600-700 m a.s.l. are influenced by a proportionally higher share of ions from distant
453 sources, while the lower sites are exposed to more local sources, especially sea spray. These findings
454 confirm that the optimal sites to study the effects of long-range pollution deposition in Svalbard are those
455 found at higher elevations sites, such as the accumulation zones of HDF or LF, because they are the least
456 impacted by the local aerosol emissions. The current study gives the first picture of the ionic composition
457 in the Svalbard snowpack in different regions across the archipelago, in the context of which processes
458 are relevant in controlling the annual snowpack chemical composition there, especially the influence of
459 local and long-range transport.

460



461 **Acknowledgements**

462 The work developed here was supported through grants 246731/E10 and 257636/E10 from the Svalbard
463 Science Forum /(Research Council of Norway), by the Gothenburg Centre of Advanced Studies, BECC -
464 Biodiversity and Ecosystem Services in a Changing Climate, Gothenburg Air and Climate Centre,
465 International Arctic Science Committee - Cryosphere working group and the Norwegian Polar Institute.
466 Part of fieldwork has been conducted thanks to the funds of the Leading National Research Centre
467 (KNOW) in Poland, received by the Centre for Polar Studies for the period 2014–2018. This research
468 was also partially supported within statutory activities No 3841/E-41/S/2020 of the Ministry of Science
469 and Higher Education of Poland. The project has received further funding from the European Union's
470 Horizon 2020 research and innovation programme under grant agreement no. 689443 via project iCUPE
471 (Integrative and Comprehensive Understanding on Polar Environments).
472



473 **REFERENCES**

474

- 475 Aas, K. S., Dunse, T., Collier, E., Schuler, T. V., Berntsen, T. K., Kohler, J., and Luks, B.: The climatic
476 mass balance of Svalbard glaciers: a 10-year simulation with a coupled atmosphere–glacier mass
477 balance model, *The Cryosphere*, 10, 1089–1104, 2016.
- 478 Ardyna, M., Babin, M., Gosselin, M., Devred, E., Bélanger, S., Matsuoka, A., and Tremblay, J.-E.:
479 Parameterization of vertical chlorophyll a in the Arctic Ocean: impact of the subsurface chlorophyll
480 maximum on regional, seasonal, and annual primary production estimates, *Biogeosciences*, 10, 4383–
481 4404, 2013.
- 482 Barbante, C., Spolaor, A., Cairns, W. R. L., and Boutron, C.: Man's footprint on the Arctic environment
483 as revealed by analysis of ice and snow, *Earth-Sci Rev*, 168, 218–231, 2017.
- 484 Barbaro, E., Spolaor, A., Karroca, O., Park, K.-T., Martma, T., Isaksson, E., Kohler, J., Gallet, J. C.,
485 Bjorkman, M. P., Cappelletti, D., Spreen, G., Zangrando, R., Barbante, C., and Gambaro, A.: Free
486 amino acids in the Arctic snow and ice core samples: Potential markers for paleoclimatic studies, *Sci*
487 *Total Environ*, 607–608, 454–462, 2017.
- 488 Barrie, L. A.: Arctic air pollution: An overview of current knowledge, *Atmospheric Environment (1967)*,
489 20, 643–663, 1986.
- 490 Björkman, M. P., Vega, C. P., Kühnel, R., Spataro, F., Ianniello, A., Esposito, G., Kaiser, J., Marca, A.,
491 Hodson, A., Isaksson, E., and Roberts, T. J.: Nitrate postdeposition processes in Svalbard surface
492 snow, *Journal of Geophysical Research: Atmospheres*, 119, 12,953–912,976, 2014.
- 493 Brage, B. H., Ketil Isaksen, Rasmus E. Benestad, Jack Kohler, Áshild Ø Pedersen, Leif E Loe, Stephen
494 J. Coulson, Jan Otto Larsen, and Varpe, Ø.: Warmer and wetter winters: characteristics and
495 implications of an extreme weather event in the High Arctic, *Environ. Res. Lett.*, 9, 2014.
- 496 Brimblecombe, P., Clegg, S. L., Davies, T. D., Shooter, D., and Tranter, M.: Observations of the
497 preferential loss of major ions from melting snow and laboratory ice, *Water Research*, 21, 1279–1286,
498 1987.
- 499 Cogley, J. G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G.
500 Kaser, M. Möller, Nicholson, L., and Zemp, M.: Glossary of Glacier Mass Balance and Related
501 Terms, IHP-VII Technical Documents in Hydrology, IACS Contribution No. 2, Unesco-IHP, Paris,
502 86, 2011.
- 503 Curtis, C. J., Kaiser, J., Marca, A., Anderson, N. J., Simpson, G., Jones, V., and Whiteford, E.: Spatial
504 variations in snowpack chemistry, isotopic composition of NO₃⁻ and nitrogen deposition from the
505 ice sheet margin to the coast of western Greenland, *Biogeosciences*, 15, 529–550, 2018.
- 506 Dahlke, S., Hughes, N. E., Wagner, P. M., Gerland, S., Wawrzyniak, T., Ivanov, B., and Maturilli, M.:
507 The observed recent surface air temperature development across Svalbard and concurring footprints
508 in local sea ice cover, *International Journal of Climatology*, n/a, 2020.
- 509 Dallmann, W. K.: The geology of Svalbard, Norwegian Polar Institute, 1999.
- 510 Eastwood, M. L., Cremel, S., Wheeler, M., Murray, B. J., Girard, E., and Bertram, A. K.: Effects of
511 sulfuric acid and ammonium sulfate coatings on the ice nucleation properties of kaolinite particles,
512 *Geophys Res Lett*, 36, 2009.
- 513 Eneroth, K., Kjellström, E., and Holmén, K.: A trajectory climatology for Svalbard; investigating how
514 atmospheric flow patterns influence observed tracer concentrations, *Physics and Chemistry of the*
515 *Earth, Parts A/B/C*, 28, 1191–1203, 2003.
- 516 Fibiger, D. L., Dibb, J. E., Chen, D., Thomas, J. L., Burkhart, J. F., Huey, L. G., and Hastings, M. G.:
517 Analysis of nitrate in the snow and atmosphere at Summit, Greenland: Chemistry and transport,
518 *Journal of Geophysical Research: Atmospheres*, 121, 5010–5030, 2016.
- 519 Forland, E. J., Benestad, R., Hanssen-Bauer, I., Haugen, J. E., and Skaugen, T. E.: Temperature and
520 Precipitation Development at Svalbard 1900–2100, *Advances in Meteorology*, 2011, 14,
521 2011.
- 522 Forsström, S., Ström, J., Pedersen, C. A., Isaksson, E., and Gerland, S.: Elemental carbon distribution in
523 Svalbard snow, *Journal of Geophysical Research: Atmospheres*, 114, 2009.
- 524 Gallet, J. C., Bjorkman, M. P., Larose, C., Luks, B., Martma, T., and Zdanowicz, C.: Protocols and
525 recommendations for the measurement of snow physical properties, and sampling of snow for black
526 carbon, water isotopes, major ions and microorganisms, *Norsk Polarinstitutt*, 46, 2018.



- 527 Gibson, E. R., Hudson, P. K., and Grassian, V. H.: Physicochemical Properties of Nitrate Aerosols:
528 Implications for the Atmosphere, *The Journal of Physical Chemistry A*, 110, 11785-11799, 2006.
- 529 Gondwe, M., Krol, M., Gieskes, W., Klaassen, W., and de Baar, H.: The contribution of ocean-leaving
530 DMS to the global atmospheric burdens of DMS, MSA, SO₂, and NSS SO₄⁼, *Global Biogeochem*
531 *Cy*, 17, 2003.
- 532 Goto-Azuma, K., Nakawo, M., Jinkang, H., Watanabe, O., and Azuma, N.: Melt-induced relocation of
533 ions in glaciers and in a seasonal snowpack, *Snow Ice Cover. Interact with Atmos. Ecosyst.*, 223,
534 287-297, 1994.
- 535 Hodgkins, R. and Tranter, M.: Solute in high arctic glacier snow cover and its impact on runoff
536 chemistry, *Annals of Glaciology*, 26, 156-160, 2017.
- 537 Isaksen, K., Nordli, Ø., Førland, E. J., Łupikasza, E., Eastwood, S., and Niedźwiedź, T.: Recent warming
538 on Spitsbergen—Influence of atmospheric circulation and sea ice cover, *Journal of Geophysical*
539 *Research: Atmospheres*, 121, 11,913-911,931, 2016.
- 540 Isaksson, E., Hermanson, M., Hicks, S., Igarashi, M., Kamiyama K, Moore, J., Motoyama, H., Muir, D.,
541 Pohjola, V., Vaikmae, R., Van de Wal, R. S. W., and Watanabe, O.: Ice cores from Svalbard—useful
542 archives of past climate and pollution history, 28, 1217-1228, 2003.
- 543 Jacobi, H. W., Obleitner, F., Da Costa, S., Ginot, P., Eleftheriadis, K., Aas, W., and Zanatta, M.:
544 Deposition of ionic species and black carbon to the Arctic snowpack: combining snow pit
545 observations with modeling, *Atmos. Chem. Phys.*, 19, 10361-10377, 2019.
- 546 Karl, M., Leck, C., Mashayekhy Rad, F., Bäcklund, A., Lopez-Aparicio, S., and Heintzenberg, J.: New
547 insights in sources of the sub-micrometre aerosol at Mt. Zeppelin observatory (Spitsbergen) in the
548 year 2015, *Tellus B: Chemical and Physical Meteorology*, 71, 1613143, 2019.
- 549 Kekonen, T., Moore, J., Perämäki, P., Mulvaney, R., Isaksson, E., Pohjola, V., and van de Wal, R. S. W.:
550 The 800 year long ion record from the Lomonosovfonna (Svalbard) ice core, *Journal of Geophysical*
551 *Research: Atmospheres*, 110, 2005.
- 552 Kekonen, T., Moore, J. C., Mulvaney, R., Isaksson, E., Pohjola, V., and van de Wal, R. S. W.: A 800
553 year record of nitrate from the Lomonosovfonna ice core, Svalbard, *Annals of Glaciology*, 35, 261-
554 265, 2017.
- 555 Keslinka, L. K., Wojczulanis-Jakubas, K., Jakubas, D., and Neubauer, G.: Determinants of the little auk
556 (*Alle alle*) breeding colony location and size in W and NW coast of Spitsbergen, *PLOS ONE*, 14,
557 e0212668, 2019.
- 558 Kuhn, M.: The nutrient cycle through snow and ice, a review, *Aquatic Sciences*, 63, 150-167, 2001.
- 559 Kühnel, R., Roberts, T. J., Björkman, M. P., Isaksson, E., Aas, W., Holmén, K., and Ström, J.: 20-Year
560 Climatology of NO₃ and NH₄⁺ Wet Deposition at Ny-Alesund, Svalbard, *Advances in Meteorology*,
561 2011, 10, 2011.
- 562 Law, K. S. and Stohl, A.: Arctic Air Pollution: Origins and Impacts, *Science*, 315, 1537, 2007.
- 563 Maturilli, M., Herber, A., and König-Langlo, G.: Climatology and time series of surface meteorology in
564 Ny-Ålesund, Svalbard, *Earth Syst. Sci. Data*, 5, 155-163, 2013.
- 565 Millero, F. J., Feistel, R., Wright, D. G., and McDougall, T. J.: The composition of Standard Seawater
566 and the definition of the Reference-Composition Salinity Scale, *Deep Sea Research Part I:*
567 *Oceanographic Research Papers*, 55, 50-72, 2008.
- 568 Möller, M. and Kohler, J.: Differing Climatic Mass Balance Evolution Across Svalbard Glacier Regions
569 Over 1900–2010, *Frontiers in Earth Science*, 6, 128, 2018.
- 570 Nawrot, A. P., Migala, K., Luks, B., Pakszys, P., and Głowacki, P.: Chemistry of snow cover and acidic
571 snowfall during a season with a high level of air pollution on the Hans Glacier, Spitsbergen, *Polar*
572 *Science*, 10, 249-261, 2016.
- 573 Nordli, Ø., Przybylak, R., Ogilvie, A. E. J., and Isaksen, K.: Long-term temperature trends and
574 variability on Spitsbergen: the extended Svalbard Airport temperature series, 1898–2012, *Polar Res*,
575 33, 21349, 2014.
- 576 Peterson, P. K., Hartwig, M., May, N. W., Schwartz, E., Rigor, I., Ermold, W., Steele, M., Morison, J.
577 H., Nghiem, S. V., and Pratt, K. A.: Snowpack measurements suggest role for multi-year sea ice
578 regions in Arctic atmospheric bromine and chlorine chemistry, *Elem Sci Anth*, 7(1), 14, 2019.
- 579 Pohjola, V. A., Moore, J. C., Isaksson, E., Jauhiainen, T., van de Wal, R. S. W., Martma, T., Meijer, H.
580 A. J., and Vaikmae, R.: Effect of periodic melting on geochemical and isotopic signals in an ice core



- 581 from Lomonosovfonna, Svalbard, *Journal of Geophysical Research: Atmospheres*, 107, ACL 1-1-
582 ACL 1-14, 2002.
- 583 Rinke, A., Maturilli, M., Graham, R. M., Matthes, H., Handorf, D., Cohen, L., Hudson, S. R., and
584 Moore, J. C.: Extreme cyclone events in the Arctic: Wintertime variability and trends, *Environ Res*
585 *Lett*, 12, 094006, 2017.
- 586 Schaap, M., van Loon, M., ten Brink, H. M., Dentener, F. J., and Builtjes, P. J. H.: Secondary inorganic
587 aerosol simulations for Europe with special attention to nitrate, *Atmos. Chem. Phys.*, 4, 857-874,
588 2004.
- 589 Schüpbach, S., Fischer, H., Bigler, M., Erhardt, T., Gfeller, G., Leuenberger, D., Mini, O., Mulvaney, R.,
590 Abram, N. J., Fleet, L., Frey, M. M., Thomas, E., Svensson, A., Dahl-Jensen, D., Kettner, E., Kjaer,
591 H., Seierstad, I., Steffensen, J. P., Rasmussen, S. O., Vallelonga, P., Winstrup, M., Wegner, A.,
592 Twarloh, B., Wolff, K., Schmidt, K., Goto-Azuma, K., Kuramoto, T., Hirabayashi, M., Uetake, J.,
593 Zheng, J., Bourgeois, J., Fisher, D., Zhiheng, D., Xiao, C., Legrand, M., Spolaor, A., Gabrieli, J.,
594 Barbante, C., Kang, J. H., Hur, S. D., Hong, S. B., Hwang, H. J., Hong, S., Hansson, M., Iizuka, Y.,
595 Oyabu, I., Muscheler, R., Adolphi, F., Maselli, O., McConnell, J., and Wolff, E. W.: Greenland
596 records of aerosol source and atmospheric lifetime changes from the Eemian to the Holocene, *Nature*
597 *Communications*, 9, 1476, 2018.
- 598 Semb, A., Brækkan, R., and Joranger, E.: Major ions in Spitsbergen snow samples, *Geophys Res Lett*,
599 11, 445-448, 1984.
- 600 Spolaor, A., Barbaro, E., Cappelletti, D., Turetta, C., Mazzola, M., Giardi, F., Björkman, M. P.,
601 Lucchetta, F., Dallo, F., Pfaffhuber, K. A., Angot, H., Dommergue, A., Maturilli, M., Saiz-Lopez, A.,
602 Barbante, C., and Cairns, W. R. L.: Diurnal cycle of iodine, bromine, and mercury concentrations in
603 Svalbard surface snow, *Atmos. Chem. Phys.*, 19, 13325-13339, 2019.
- 604 Spolaor, A., Barbaro, E., Christille, J. M., Kirchgeorg, T., Giardi, F., Cappelletti, D., Turetta, C.,
605 Bernagozzi, A., Björkman, M. P., Bertolini, E., and Barbante, C.: Evolution of the Svalbard annual
606 snow layer during the melting phase, *Rendiconti Lincei*, doi: 10.1007/s12210-015-0500-8, 2016. 1-8,
607 2016.
- 608 Spolaor, A., Gabrieli, J., Martma, T., Kohler, J., Björkman, M. B., Isaksson, E., Varin, C., Vallelonga,
609 P., Plane, J. M. C., and Barbante, C.: Sea ice dynamics influence halogen deposition to Svalbard, *The*
610 *Cryosphere*, 7, 1645-1658, 2013.
- 611 Spolaor, A., Vallelonga, P., Gabrieli, J., Martma, T., Björkman, M. P., Isaksson, E., Cozzi, G., Turetta,
612 C., Kjær, H. A., Curran, M. A. J., Moy, A. D., Schönhardt, A., Blechschmidt, A. M., Burrows, J. P.,
613 Plane, J. M. C., and Barbante, C.: Seasonality of halogen deposition in polar snow and ice, *Atmos.*
614 *Chem. Phys.*, 14, 9613-9622, 2014.
- 615 Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Henderson, K. A., Brecher, H. H., Zagorodnov,
616 V. S., Mashiota, T. A., Lin, P.-N., Mikhalevko, V. N., Hardy, D. R., and Beer, J. r.: Kilimanjaro Ice
617 Core Records: Evidence of Holocene Climate Change in Tropical Africa, *Science*, 298, 589-593,
618 2002.
- 619 Trachsel, J. C., Avak, S. E., Edebeli, J., Schneebeli, M., Bartels-Rausch, T., Bruetsch, S., and Eichler,
620 A.: Microscale Rearrangement of Ammonium Induced by Snow Metamorphism, *Frontiers in Earth*
621 *Science*, 7, 194, 2019.
- 622 van Pelt, W., Pohjola, V., Pettersson, R., Marchenko, S., Kohler, J., Luks, B., Hagen, J. O., Schuler, T.,
623 V., Dunse, T., Noël, B., and Reijmer, C.: A long-term dataset of climatic mass balance, snow
624 conditions, and runoff in Svalbard (1957–2018), *The Cryosphere*, 13, 2259-2280, 2019.
- 625 Vecchiato, M., Barbaro, E., Spolaor, A., Burgay, F., Barbante, C., Piazza, R., and Gambaro, A.:
626 Fragrances and PAHs in snow and seawater of Ny-Ålesund (Svalbard): Local and long-range
627 contamination, *Environmental Pollution*, 242, 1740-1747, 2018.
- 628 Vega, C. P., Björkman, M. P., Pohjola, V. A., Isaksson, E., Pettersson, R., Martma, T., Marca, A., and
629 Kaiser, J.: Nitrate stable isotopes in snow and ice samples from four Svalbard sites, *Polar Res*, 34,
630 2015a.
- 631 Vega, C. P., Pohjola, V. A., Beaudon, E., Claremar, B., van Pelt, W. J. J., Pettersson, R., Isaksson, E.,
632 Martma, T., Schwikowski, M., and Bøggild, C. E.: A synthetic ice core approach to estimate ion
633 relocation in an ice field site experiencing periodical melt; a case study on Lomonosovfonna,
634 Svalbard, *The Cryosphere Discuss.*, 9, 5053-5095, 2015b.



- 635 Virkkunen, K., Moore, J. C., Isaksson, E., Pohjola, V., Perämäki, P., Grinsted, A., and Kekonen, T.:
636 Warm summers and ion concentrations in snow: comparison of present day with Medieval Warm
637 Epoch from snow pits and an ice core from Lomonosovfonna, Svalbard, *J Glaciol*, 53, 623-634, 2007.
638 Winther, J.-G., Bruland, O., Sand, K., Gerland, S., Marechal, D., Ivanov, B., Gøowacki, P., and König,
639 M.: Snow research in Svalbard—an overview, *Polar Res*, 22, 125-144, 2003.
640 Winther, M., Christensen, J. H., Plejdrup, M. S., Ravn, E. S., Eriksson, Ó. F., and Kristensen, H. O.:
641 Emission inventories for ships in the arctic based on satellite sampled AIS data, *Atmos Environ*, 91,
642 1-14, 2014.
643 Wojczulanis K., Jakubas D., and Stempniewicz, L.: Avifauna of Hornsund area, SW Spitsbergen: present
644 state and recent changes, *Polish Polar Research*, 29, 187-197, 2008.
645 Wolff, E. W., Barbante, C., Becagli, S., Bigler, M., Boutron, C. F., Castellano, E., De Angelis, M.,
646 Federer, U., Fischer, H., and Fundel, F.: Changes in environment over the last 800,000 years from
647 chemical analysis of the EPICA Dome C ice core, *Quaternary Sci Rev*, 29, 285-295, 2010.
648 Zhuang, H., Chan, C. K., Fang, M., and Wexler, A. S.: Formation of nitrate and non-sea-salt sulfate on
649 coarse particles, *Atmos Environ*, 33, 4223-4233, 1999.
650
651



652 **TABLES**

653 **Table 1.** Table 1. Iaciers and sampling sites included in this study with their main characteristic. AWS:
654 atmospheric weather station; UiO: University of Oslo; ThèMA: Thèoriser & Modèliser pour Amènager,
655 University of Franche-Comté; NPI: Norwegian Polar Institute; IMAU: Institute for Marine and Atmospheric
656 Research, Utrecht University; UoS: University of Silesia, IG PAS – Institute of Geophysics, Polish
657 Academy of Sciences; CNR – Consiglio Nazionale delle Ricerche. . The seven glaciers were considered at
658 three different altitudes: 1) lower ablation zone; 2) ELA; 3) upper accumulation zone. Exceptionally, two
659 snow pits (KVG 1 and KVG 1.5) were dug in the ablation zone of Kongsvegen glacier.

660

661 **Table 2.** Total load (mg m^{-2}) of major ions, calculated as the sum of loads in all layers of each snow pit. Sea
662 salt sulphate (ss-SO_4^{2-}) and non-sea-salt sulphate (nss-SO_4^{2-}) are expressed as mg m^{-2} , while chloride
663 depletion (Cl_{dep}^+) is given as a percentage and bromide enrichment (Br_{enr}) refers to an enrichment compare to
664 sea water. Average SWE-weighted stable water isotope ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and average deuterium excess
665 (d) are also reported.

666

667 **Table 3.** Chemical loads (mg m^{-2}) of selected elements from the 2016 sampling and earlier studies
668 at Lomonosovfonna summit (LF3), corresponding to the concentrations given in Fig. 4.

669

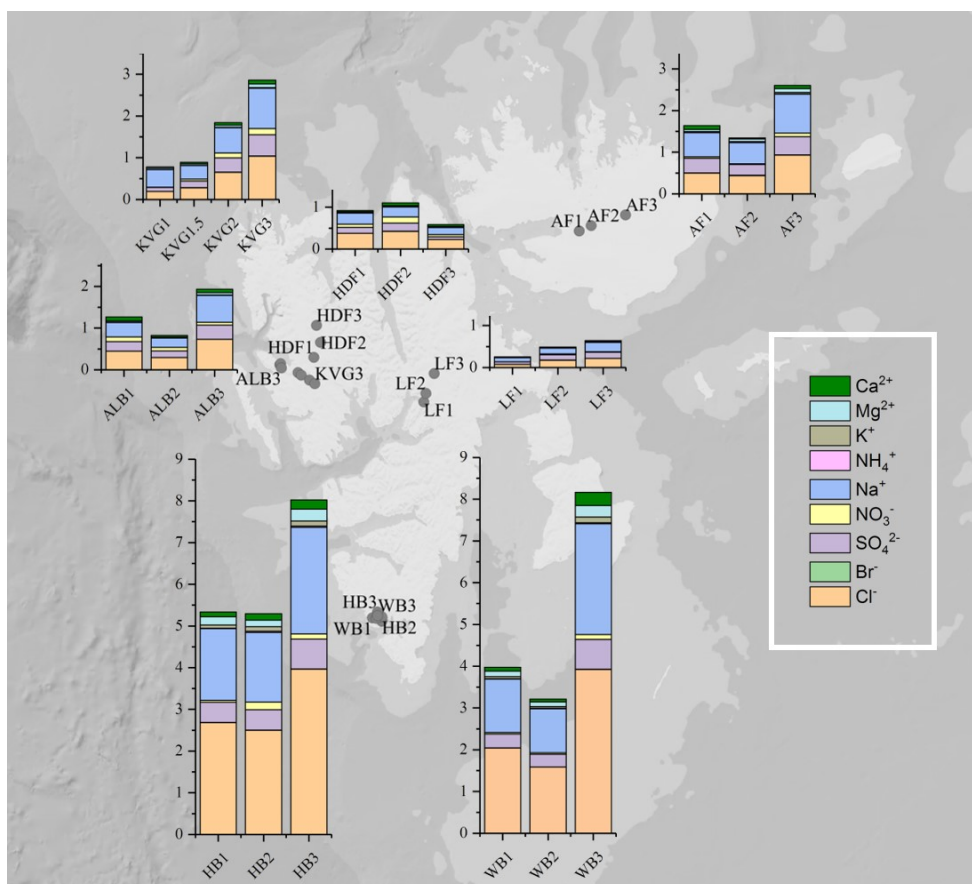
670 **Table 4.** Spearman rank order correlations for all 7 glaciers ($n=22$ locations) with a $p < 0.05$: a) of total loads
671 (mg m^{-2}) of major ions (calculated as the sum of loads in all layers of each snow pit), b) of volume-weighted
672 average concentrations of each snow pit, calculated by dividing the total load of each snow pit by its total
673 water equivalent. Non-sea-salt (nss) components were calculated based on the seawater ratios to Na^+ (0.038
674 and 0.252, respectively, for Ca^{2+} and SO_4^{2-} in mg L^{-1} ; Millero et al. 2008); ns = not significant with p -value
675 > 0.05 .



676 **FIGURES**

677

678 **Figure 1.** Total snowpack loads (mg m^{-2}) of major ions in 22 snow pits collected on glaciers during the C2S3
679 project. Seven glaciers were sampled in three snow pits in the lower ablation zone (1), near the equilibrium
680 line (2) and in the upper accumulation zone (3), except on Kongsvegen glacier (KVG) where there was an
681 extra snow pit sampled within the ablation zone. Glacier site abbreviations are given in Table 1.



682

683

684

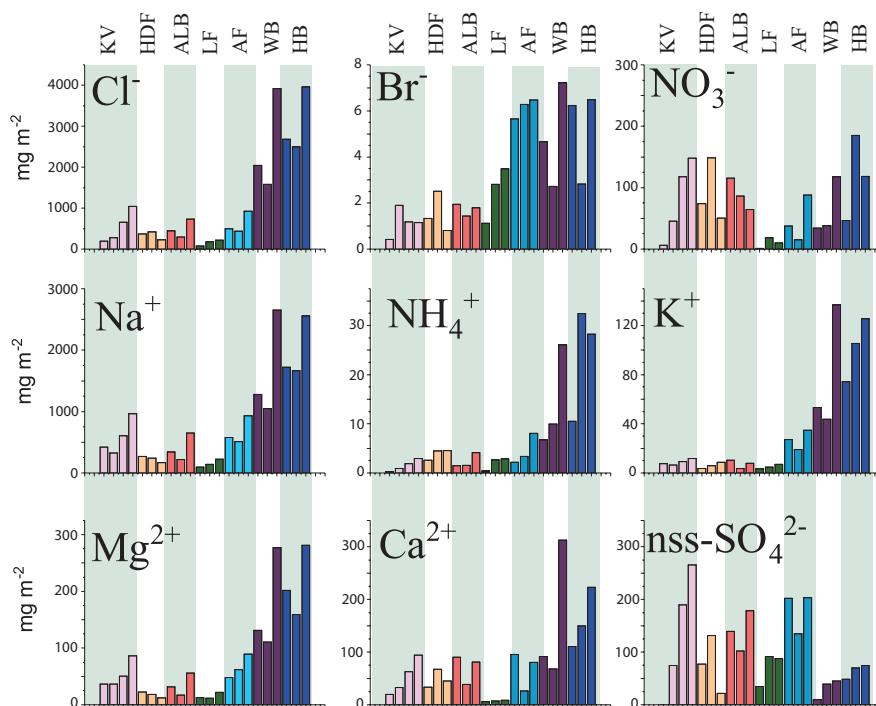
685

686

687



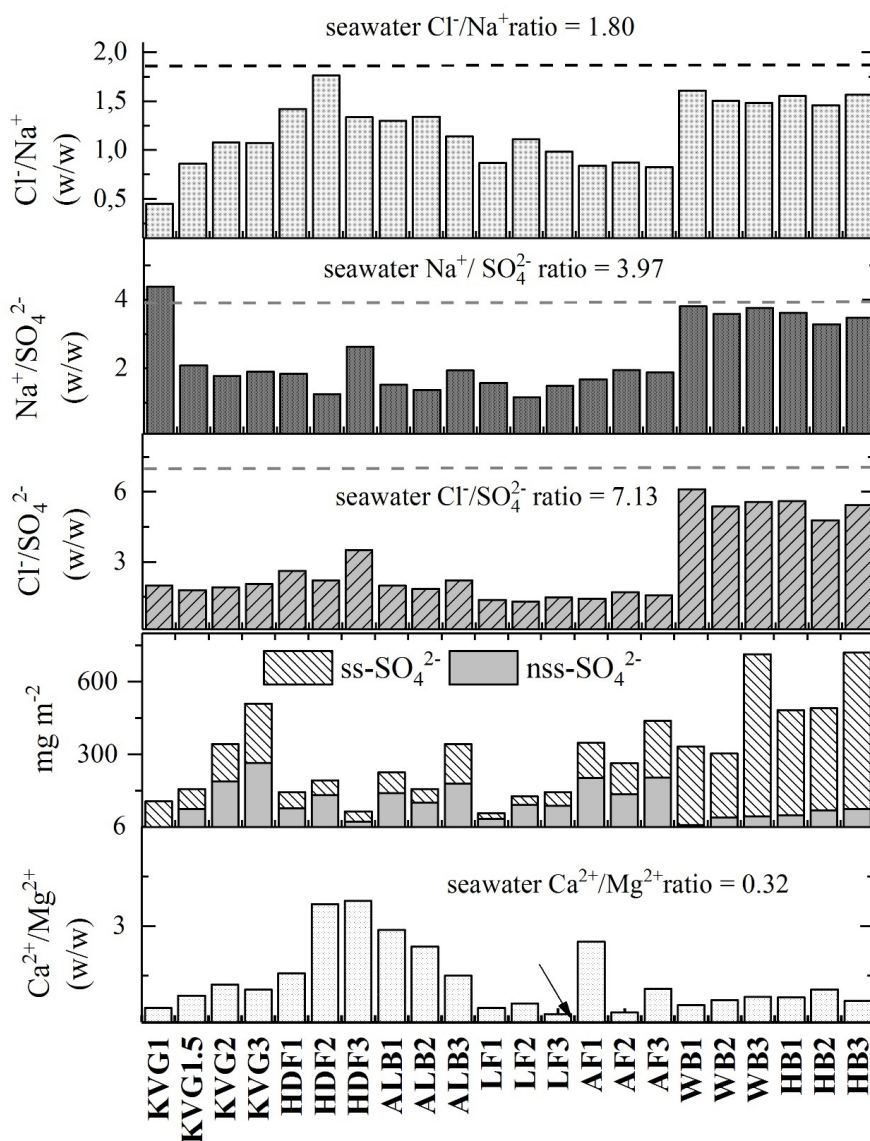
688 **Figure 2.** Calculated ionic loads in the snowpack (mg m^{-2}) at the 7 glacier sites sampled during the C2S3
689 project. Snow pits for each glacier are marked with the same colour and ordered from lower (left) to higher
690 altitudes (right). For the KGV another snow pit was dug between glaciers zone 1 and 2.
691



692
693
694
695
696
697
698
699
700
701
702



703 **Figure 3.** Panels from top: 1) Cl^-/Na^+ ; 2) $\text{Na}^+/\text{SO}_4^{2-}$; 3) $\text{Cl}^-/\text{SO}_4^{2-}$; 4) the total loads of sea-salt sulphate (ss-
 704 SO_4^{2-}) and non-sea-salt sulphate (nss- SO_4^{2-}), and 5) $\text{Ca}^{2+}/\text{Mg}^{2+}$ - for all glaciers investigated during the C2S3
 705 project (in the spring 2016).
 706
 707



708



709

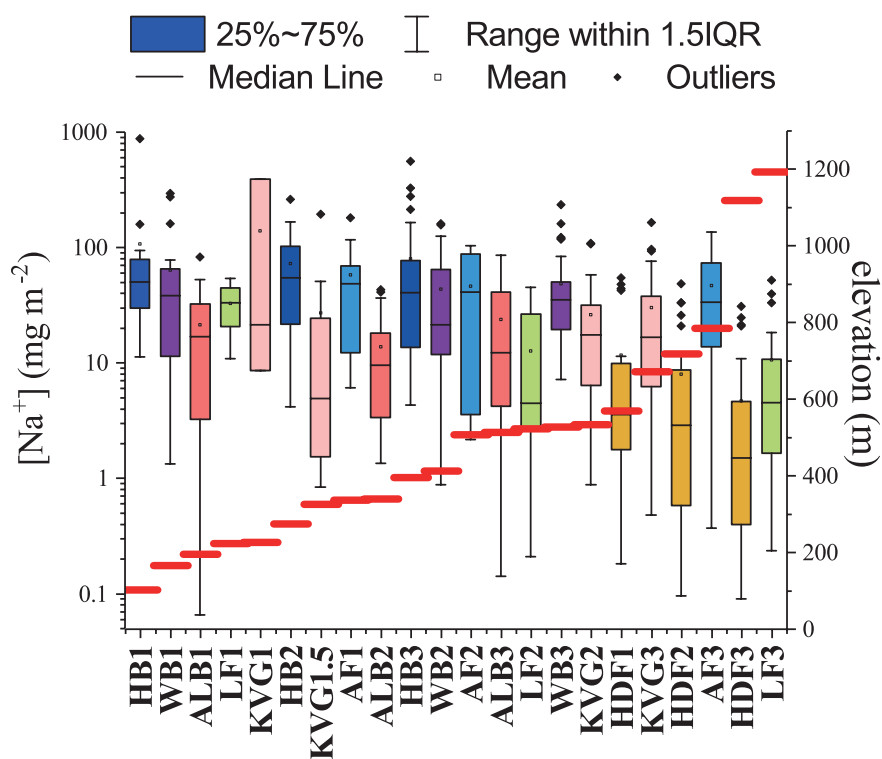
710 **Figure 4.** Sodium load in snow pits ordered by increasing elevation in m a.s.l., indicated by the red lines.

711 The colours identify areas where the snow pits have been excavated: each colour represents a separate glacier

712 (HB – blue; WB – purple; ALB – red; LF – green; KVG – pink; AF – light blue; HDF – orange). IQR =

713 inter-quartile range, i.e. the difference between the value of quartiles 3 and 1.

714



715

716

717

718

719

720

721

722

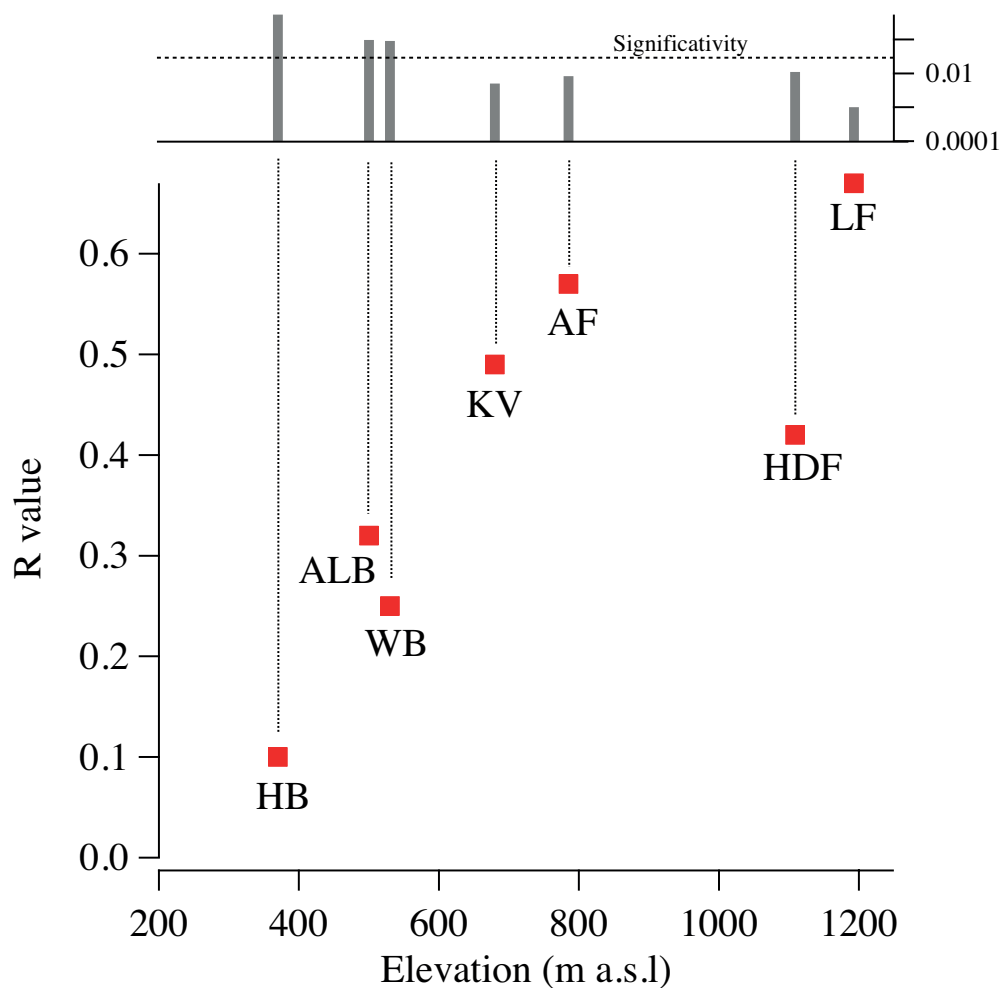
723

724



725

726 **Figure 5.** The correlation coefficient between oxygen isotope ratio ($\delta^{18}\text{O}$) and $\log[\text{Na}_{\text{load}}]$ increases with
727 elevation. The left axis represents the correlation coefficient (R) between $\log[\text{Na}_{\text{load}}]$ and $\delta^{18}\text{O}$, using the
728 entire dataset for each snow pit (i.e. all layers have been used for the statistical correlation). The *x axis*
729 indicates the altitude of the snow pit. The upper panel shows the p-value: correlations have been considered
730 statistically significant if $p < 0.05$.



731

732



Table 1. Glaciers and sampling sites included in this study with their main characteristics. AWS: automatic weather station; UiO: University of Oslo; ThéMA: Théoriser & Modéliser pour Aménager, Université de Franche-Comté; NPI: Norwegian Polar Institute; IMAU: Institute for Marine and Atmospheric Research, Utrecht University; UoS: University of Silesia, IG PAS – Institute of Geophysics, Polish Academy of Sciences; CNR – Consiglio Nazionale delle Ricerche.

Glacier	Site	Zone	Lat. (°N)	Lon. (°E)	Elev. (m)	Date (dd.mm.yyyy)	AWS		
							Air Temp. (°C)	Snow height (cm)	
Austfonna	AF1	ablation	79.734	22.414	336	21.04.2016	-13.5	106	330.50
	AF2	equilibrium line	79.767	22.825	507	23.04.2016	-7.1	135	439.59
	AF3	accumulation	79.832	24.004	785	24.04.2016	-14.7	181	803.93
Austre Lovénbreen	ALB1	ablation	78.883	12.136	195	25.04.2016	-3.7	81	296.66
	ALB2	equilibrium line	78.889	12.159	340	25.04.2016	-2.8	90	353.17
	ALB3	accumulation	78.861	12.187	513	20.04.2016	-11.3	161	499.67
Kongsvegen	KVG1	ablation	78.830	12.759	226	13.04.2016	-13.9	20	51.29
	KVG1.5	ablation	78.813	12.869	326	13.04.2016	-13.9	75	261.94
	KVG 2	equilibrium line	78.780	13.153	534	11.04.2016	-17.5	162	575.78
	KVG3	accumulation	78.756	13.336	672	12.04.2013	-15.5	234	880.13
Holtedahlfonna	HDF1	ablation	78.931	13.303	570	17.04.2016	-14.5	108	372.98
	HDF2	equilibrium line	79.029	13.531	718	17.04.2016	-14.2	175	625.00
	HDF3	accumulation	79.140	13.394	1119	15.04.2016	-18.1	201	732.08
Lomonosovfonna	LF1	ablation	78.633	17.077	223	10.04.2016	-10.9	27	99.4
	LF2	equilibrium line	78.691	17.150	523	9.04.2016	-5.8	94	277.28
	LF3	accumulation	78.824	17.435	1193	11.04.2016	-24	146	487.01
Hansbreen	HB1	ablation	77.049	15.639	102	25.04.2016	-7.3	102	396.10
	HB2	equilibrium line	77.083	15.639	275	25.04.2016	-6.9	169	640.28
	HB3	accumulation	77.120	15.487	396	29.04.2016	0.7	288	1305.09
Werenskiöldbreen	WB1	ablation	77.075	15.313	166	16.04.2016	-9.2	81	328.34
	WB2	equilibrium line	77.072	15.441	413	16.04.2016	-11.2	110	454.75
	WB3	accumulation	77.092	15.489	528	18.04.2016	-11.1	330	1396.60



Table 2. Total load (mg m^{-2}) of major ions, calculated as the sum of loads in all layers of each snow pit. Sea salt sulphate (ss-SO_4^{2-}) and non-sea-salt sulphate (nss-SO_4^{2-}) are expressed as mg m^{-2} , while chloride depletion ($\text{Cl}_{\text{dep}}^{\%}$) is given as a percentage and bromide enrichment (Br_{enr}) refers to an enrichment compare to sea water. Average SWE-weighted stable water isotope ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and average deuterium excess (d) are also reported.

	Cl ⁻	Br ⁻	SO ₄ ²⁻	NO ₃ ⁻	Na ⁺	NH ₄ ⁺	K ⁺	Mg ²⁺	Ca ²⁺	ss-SO ₄ ²⁻	nss-SO ₄ ²⁻	Cl _{dep} [%]	Br _{enr}	δ ¹⁸ O	δ ² H	d
KVG1	190	0.4	96	6	421	0.3	7	37	20	106	nd	75	0.2	-9.69	-66.17	11.37
KVG1.5	281	1.9	157	45	327	0.9	6	36	33	82	75	52	1.0	-11.32	-78.25	12.34
KVG2	652	1.2	342	118	605	1.9	9	51	63	152	190	40	0.3	-12.51	-88.62	11.48
KVG3	1039	1.2	509	148	967	2.9	12	86	94	244	266	40	0.2	-12.72	-89.50	12.25
HDF1	373	1.3	144	74	267	2.6	4	23	33	68	79	21	0.9	-13.51	-94.37	13.75
HDF2	423	2.5	192	148	240	4.5	6	18	67	61	131	2	1.7	-13.91	-99.15	12.10
HDF3	227	0.8	65	51	170	4.5	9	12	45	43	22	25	0.8	-15.18	-104.51	16.97
ALB1	446	1.9	226	115	343	1.5	10	31	90	86	139	27	0.9	-11.22	-75.17	14.59
ALB2	294	1.4	158	87	221	1.6	4	17	38	56	107	25	1.2	-12.19	-83.11	14.40
ALB3	729	1.8	342	64	648	4.2	8	56	81	158	165	36	0.4	-12.40	-85.40	13.79
LF1	75	1.1	59	1	95	0.4	3	12	6	31	48	51	2.1	-11.61	-82.79	10.10
LF2	174	2.8	127	18	141	2.6	5	12	7	53	127	38	3.2	-14.54	-105.44	10.90
LF3	216	3.5	144	10	225	2.9	7	22	9	56	93	45	2.7	-15.14	-110.42	10.69
AF1	498	5.7	348	38	578	2.2	27	48	95	127	173	53	1.6	-14.34	-100.76	13.94
AF2	438	6.3	263	15	509	3.4	19	62	26	147	153	51	2.0	-16.00	-111.15	16.84
AF3	928	6.5	439	88	933	8.1	35	89	81	185	206	54	1.5	-13.89	-96.89	14.24
WB1	2041	4.7	332	34	1278	6.7	53	131	91	340	15	10	0.6	-10.17	-70.62	10.75
WB2	1584	2.7	304	38	1051	9.9	44	110	68	220	24	16	0.4	-10.25	-70.14	11.90
WB3	3922	7.2	713	118	2649	26.1	137	277	313	671	37	17	0.5	-9.54	-63.64	12.66
HB1	2680	6.2	482	46	1722	10.5	74	201	110	475	47	13	0.6	-11.14	-75.93	13.19
HB2	2499	2.8	490	185	1667	32.5	105	159	150	350	73	19	0.3	-10.69	-73.34	12.17
HB3	3964	6.5	719	118	2557	28.2	125	281	223	751	107	13	0.4	-11.25	-77.62	12.35



Table 3. Loads (mg m^{-3}) of selected major ions from the 2016 sampling and from earlier studies at Lomonosovfonna summit (LF3), corresponding to the concentrations given in Fig. 4.

Year	Na^+	Ca^{2+}	NO_3^-	nss- SO_4^{2-}	Study
2002	126.7	7.1	27.3	37.1	(Virkkunen et al., 2007)
2009	n.a.	n.a.	33.5	n.a.	<i>Vega C. (unpublished data)</i>
2010	80.1	24.3	52.3	48.1	<i>Vega C. (unpublished data)</i>
2011	262.9	46.2	27.2	34.1	(Vega et al., 2015), <i>Vega C. (unpublished data)</i>
2016	222.2	7.2	11.4	93.0	<i>This study</i>



Table 4. Spearman rank order correlations of a) ionic loads (mg m^{-3}) and b) SWE-weighted mean concentrations of major ions across all 7 glaciers ($n=22$ locations). ns = non-significant correlations (p -value > 0.05). Ionic loads were calculated from all snow pit layers, while SWE-weighted mean concentrations were calculated by dividing the ionic loads in each snow pit by its total SWE. Non-sea-salt (nss) components were estimated based from seawater ratios to Na^+ (0.038 and 0.252, respectively, for Ca^{2+} and SO_4^{2-} in mg L^{-1} ; Millero et al. 2008).

	Cl ⁻	Br ⁻	SO ₄ ²⁻	NO ₃ ⁻	Na ⁺	NH ₄ ⁺	K ⁺	Mg ²⁺	Ca ²⁺	nss-SO ₄ ²⁻
a)										
Br ⁻	0.53									
SO ₄ ²⁻	0.93	0.60								
NO ₃ ⁻	0.55	ns	0.55							
Na ⁺	0.94	0.48	0.92	0.44						
NH ₄ ⁺	0.73	0.62	0.68	ns	0.64					
K ⁺	0.82	0.61	0.81	ns	0.85	0.75				
Mg ²⁺	0.90	0.51	0.88	ns	0.98	0.62	0.82			
Ca ²⁺	0.86	ns	0.83	0.69	0.82	0.61	0.76	0.71		
nss-SO ₄ ²⁻	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
nss-Ca ²⁺	0.76	ns	0.75	0.77	0.68	0.56	0.66	0.56	0.96	ns
b)										
Br ⁻	ns									
SO ₄ ²⁻	0.75	0.58								
NO ₃ ⁻	ns	-0.48	ns							
Na ⁺	0.95	ns	0.80	ns						
NH ₄ ⁺	ns	ns	ns	ns	0.47					
K ⁺	0.83	0.46	0.73	ns	0.88	0.62				
Mg ²⁺	0.92	ns	0.78	ns	0.98	0.47	0.86			
Ca ²⁺	0.85	ns	0.64	0.44	0.76	ns	0.62	0.70		
nss-SO ₄ ²⁻	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
nss-Ca ²⁺	0.67	ns	0.45	0.56	0.54	ns	ns	0.47	0.91	ns