

## Snow chemistry in Svalbard, Arctic

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### Abstract

Snow samples were collected from 8 snowpits and 11 snowfall events from the Longyearbyen region, Svalbard during January to May 1996. Among major chemical species ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$ ),  $\text{Cl}^-$  and  $\text{Na}^+$ , which mainly come from sea-salt aerosol, are the dominant soluble impurities in snow. The crustal cation  $\text{Ca}^{2+}$  has the highest concentration in dirty layers of snowpack. Snow  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$  and  $\text{Na}^+$  correlate very closely and the peak values are consistent in snowpit, though their sources may be different. Snow conductivity correlates closely with  $\text{Na}^+$ ,  $\text{Cl}^-$  and  $\text{Mg}^{2+}$  and pH correlates positively with  $\text{Ca}^{2+}$  and negatively with  $\text{SO}_4^{2-}$  and  $\text{NO}_3^-$ . In general, the major ion concentrations in snowpack from Svalbard is higher compared with those in snowpack from other remote regions, such as Greenland, Antarctic and Qinghai-Tibetan Plateau, especially for  $\text{Na}^+$  and  $\text{Cl}^-$ .

### 1. Introduction

Studies on modern snow chemistry are essential for reconstructing paleoclimatic and environmental changes recorded in ice cores. In Arctic, these studies were performed mainly in Greenland Ice Sheet, including the characteristics of temporal and spatial variation of chemical species, sources, transport and deposition of impurities in surface snow and ice (Herron, 1982; Mayewski *et al.*, 1987; Davidson *et al.*, 1987, 1989; Steffensen, 1988; Beer *et al.*, 1991; Yang *et al.*, 1996).

Svalbard (74°–81°N, 10°–35°E), located in Arctic, is close to Greenland. Its area is  $6.2 \times 10^4 \text{ km}^2$  and 60% of it is covered by glaciers (ice caps) (Hisdal, 1985) (Fig. 1). Glaciological studies in Svalbard have been performed since the beginning of 20th century, and major results were limited to physics of glaciers (Kang *et al.*, 1996). Only a few studies

on snow chemistry (Gjessing, 1977; Semb *et al.*, 1984; Goto-Azuma *et al.*, 1993) and ice cores (Gordiyenko *et al.*, 1980; Fujii *et al.*, 1990; Goto-Azuma *et al.*, 1995) have been carried out in Svalbard. In Svalbard, the comparatively mild climate is usually attributed to the North Atlantic Current, which has a branch, the Norwegian Current, flowing towards the west coast of Svalbard. Great temperature differences occur between the mild, southerly air streams and the cold Arctic air invading the islands from northerly or easterly directions, and both summer snowing and winter raining can occur (Hisdal, 1985). In order to get a better understanding of the climatic and environmental change from ice core records in Svalbard, detailed studies on modern processes of snow and ice should be performed.

In this paper the snow chemistry from 8 snowpits and 11 snowfall were analyzed. The main purpose of this study is to expand the snow chemistry data base for Svalbard. A secondary goal is to investigate the relationship between chemical species in snow and discuss their sources and environmental implications.

### 2. Methodology

Snowpack samples were collected from three glaciers, Larsbreen (78°107'N, 15°345'E), Bogenbreen (78°080'N, 15°380'E) and Drogbreen (78°097'N, 17°070'E) in Longyearbyen region in Svalbard during March 3rd to May 31st, 1996 (Fig. 1). Five snowpits (pit1–pit5), two snowpits (pit6–pit7) and one snowpit (pit8) were excavated from Larsbreen, Bogenbreen and Drogbreen, respectively. The date of sampling and elevation of snowpits are showed in Table 1. All snowpits were located above the average equilibrium line on every glacier. Excepting snowpit 8 (which is the deepest pit of 2.2 m and doesn't reach the icy crust), snow samples were taken down to the icy crust corresponding to the summer melt layer at an interval of 10 cm in the snowpit wall and placed

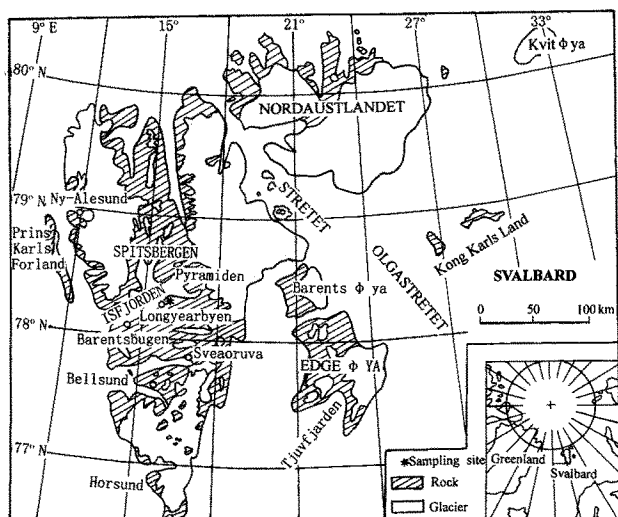


Fig. 1. Sketch map of Svalbard and the sampling site

into plastic bags after sectioning. Thus snowpit 1-7 don't include summer layer and snow chemistry is very little influenced by percolation in snowpack. By the observation of snowpit 8 in the field, there are very few ice layers contained in the pit stratigraphy, presenting that the melting is not influencing snow chemistry. Snowfall samples were collected by plastic bags directly in the eastern suburb of Longyearbyen after snowfall events. Each melted sample was transferred to high density polyethylene bottle and kept in the -20°C cold room. Samples were transported to Lanzhou from Norway and analyzed in the Laboratory of Ice Core and Cold Regions Environment, Chinese Academy of Sciences. Cations analysis ( $K^+$ ,  $Na^+$ ,  $Ca^{2+}$ , and  $Mg^{2+}$ ) was performed using PE-2380 Atomic Absorption Spectrophotometer, the detection limit of the system is 5-25 ppb (relative standard deviation less than 1%). Anions ( $Cl^-$ ,  $NO_3^-$ , and  $SO_4^{2-}$ ) were measured using DX-300 Ion Chromatography (the detection limit of 25 ppb and relative standard deviation less than 1%). Oxygen isotope, pH and conductivity analyses were performed by using a Finnigan MAT-252 Spectrometer (accuracy of 0.5 ‰), pH meter (model PHS-2) and conductivity meter (model DDS-11A), respectively.

### 3. Results and discussion

#### 3.1. Sample analysis results

Analytical results of major ion concentrations in 8 snowpits and 11 snowfall were shown in Tables 1 and 2. Due to the short span of elevation, there are no close relationship between ion concentrations and snowpits elevation. The concentrations of  $Cl^-$  and  $Na^+$  were higher than those of

other ions, indicating that the two ions were the dominant soluble impurities in precipitation in this region. "Non-sea-salt (nss)" component was calculated to understand the contribution of sea-salt and nss sources for each ion. All of  $Na^+$  is supposed to come from sea-salt in the region. According to the ratio of the ion and  $Na^+$  in Standard Ocean Water (Brewer, 1975), the nss component of the ion is calculated by:

$$\text{nss } A = A_t - Na_t (A_s / Na_s)$$

Here  $A_t$ ,  $A_s$  are the ion concentrations in the sample and Standard Ocean Water, respectively.  $Na_t$ ,  $Na_s$  are  $Na^+$  concentrations in the sample and Standard Ocean Water, respectively.

For snowpack samples, excepting  $NO_3^-$ , percentage of nss  $Ca^{2+}$  is the highest among nss ions (85%), suggesting crustal source of  $Ca^{2+}$ . Rock-surrounded valley glacier is major type in Longyearbyen region (Fig. 1) and local dust from surrounded rock may be the major sources of  $Ca^{2+}$ . 70% (in snowpack) and 98% (in snowfall) of  $Cl^-$  and 49% of  $SO_4^{2-}$  come from sea-salt source. Here sea-salt contribution of  $NO_3^-$  and  $F^-$  can be neglected.

#### 3.2. Correlation analysis of snow chemistry

The total of 113 snow samples from 8 snowpits and 11 snowfall events in Svalbard were analyzed for correlation between chemical components (Table 3). Correlation coefficients for the major ions show  $Cl^-$  and  $Na^+$  correlate very closely with a correlation coefficient of 0.90, reflecting their uniform sea-salt source.  $SO_4^{2-}$  has a good correlation with  $NO_3^-$ ,  $Cl^-$ ,  $Na^+$  and  $Mg^{2+}$  with correlation coefficient ranging from 0.52-0.78, suggesting these species may have relatively

Table 1 Mean major ion concentrations of snowpits from Longyearbyen region, Svalbard (units: ppm)

No. of snow-pit	Elevation (m a.s.l.)	Depth (cm)	No. of samples	$Na^+$	$K^+$	$Ca^{2+}$	$Mg^{2+}$	$Cl^-$	$NO_3^-$	$SO_4^{2-}$	Sampling Date (in 1996)
PIT1	570	90	9	1.027	0.219	1.036	0.137	2.142	0.240	0.401	March 5th
PIT2	700	110	11	1.228	0.207	0.066	0.120	2.419	0.274	0.511	March 5th
PIT3	650	90	9	0.798	0.119	0.141	0.104	1.505	0.240	0.419	March 26th
PIT4	570	120	12	1.514	0.161	0.305	0.242	4.019	0.242	0.735	May 10th
PIT5	700	120	12	0.662	0.112	0.660	0.239	1.484	0.135	0.361	May 10th
PIT6	400	120	12	1.044	0.144	0.421	0.106	1.373	0.226	0.355	May 14th
PIT7	620	150	15	1.722	0.178	0.268	0.217	3.532	0.338	0.888	May 14th
PIT8	600	220	22	1.850	0.928	0.222	0.181	3.282	0.201	0.589	May 31st
Average				1.256	0.270	0.381	0.167	2.500	0.239	0.539	
Non sea-salt				0	0.208	0.323	0.026	0.745	0.239	0.272	
Percent of non sea-salt (%)				0	77	85	16	30	100	51	

Table 2 Major ion concentrations of snowfall from Longyearbyen, Svalbard (units: ppm)

Snowfall Events	Date (in 1996)	$Na^+$	$K^+$	$Ca^{2+}$	$Mg^{2+}$	$Cl^-$	$NO_3^-$	$SO_4^{2-}$
1	February 25	0.525	0.115	0.051	0.064	0.736	0.976	0.736
2	February 27	0.131	0.080	0.024	0.023	0.208	0.203	0.161
3	March 2-3	2.159	0.432	0.147	0.204	5.330	0.307	0.717
4	March 5-6	2.474	0.397	0.152	0.236	3.747	0.310	0.814
5	March 10	2.043	0.454	0.144	0.207	3.063	1.476	1.941
6	March 12	0.446	0.242	0.048	0.030	0.974	0.039	0.096
7	March 18-19	0.588	0.256	0.084	0.055	0.993	0.217	0.350
8	March 19-23	5.558	-----	0.561	0.653	10.602	0.798	2.140
9	April 1-2	0.995	0.397	0.111	0.079	1.124	0.112	0.434
10	April 24-25	2.594	0.538	0.167	0.253	6.087	0.145	1.053
11	May 3-5	1.255	0.200	0.203	0.171	1.475	0.295	1.074
Average		1.706	0.311	0.154	0.180	3.122	0.443	0.865
Non sea-salt		0	0.248	0.089	0.025	0.050	0.443	0.438
Percent of non sea-salt (%)		0	80	57	14	1.6	100	51

-----: It was not measured.

Table 3 Correlation coefficients between chemical components in snow from Svalbard  
(The  $R \geq 0.34$  is significant at the 99.9% level)

	K <sup>+</sup>	Na <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	δ <sup>18</sup> O	Con.
Na <sup>+</sup>	0.54								
Ca <sup>2+</sup>	-0.06	-0.06							
Mg <sup>2+</sup>	0.19	0.34	0.34						
Cl <sup>-</sup>	0.29	0.90	-0.08	0.13					
NO <sub>3</sub> <sup>-</sup>	-0.02	0.37	-0.14	0.19	0.33				
SO <sub>4</sub> <sup>2-</sup>	0.13	0.72	-0.08	0.52	0.78	0.78			
δ <sup>18</sup> O	0.18	0.35	-0.04	0.26	0.35	0.22	0.22		
Con.	0.58	0.83	0.38	0.72	0.75	0.37	0.32	0.32	
pH	0.31	-0.09	0.57	0.17	-0.13	-0.59	-0.40	0.17	0.17

Note: Con. represents conductivity.

consistent variations. Taking snowpit 7 as a sample (Fig. 2), the variations of these species agree with each other (e.g. higher concentrations at the depth of 50–70cm) in snowpit. Though the consistent variations of species don't mean the consistent source, for nss SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup>, this may reflect the uniform source. Studies show that SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> may be contributed to mid-latitude anthropogenic pollution transporting to Arctic in spring (Semb *et al.*, 1984; Joranger *et al.*, 1984; Beer *et al.*, 1991; Heintzenberg *et al.*, 1994). Snow δ<sup>18</sup>O has a positive correlation with sea-salt species (Cl<sup>-</sup> and Na<sup>+</sup>). Studies in Greenland suggest that snow δ<sup>18</sup>O correlates positively with temperature and is higher in summer and lower in winter (Beer *et al.*, 1991). Due to the short term sampling, the relationship between δ<sup>18</sup>O and temperature is not confirmed in this study. The positive relationship between δ<sup>18</sup>O and sea-salt species may be related to precipitation origins from marine air mass. In Figure 2, the highest Ca<sup>2+</sup> concentration is corresponding to the visible dirty layer, confirming further that Ca<sup>2+</sup> comes from the local crustal dust.

Conductivity is a parameter, which depends on the total dissolved solids of a solution. Due to the domination of sea-salt ions (e.g. Na<sup>+</sup>, Cl<sup>-</sup> and Mg<sup>2+</sup>) among major species in snow, the conductivity correlates closely with Na<sup>+</sup>, Cl<sup>-</sup> and Mg<sup>2+</sup> with correlation coefficients ranging from 0.72–0.83 (Table 3). Snow pH is determined by a host of acids (H<sub>2</sub>SO<sub>4</sub>, HNO<sub>3</sub>, HCOOH, etc.) and bases (NH<sub>3</sub> and CaCO<sub>3</sub>) (Galloway *et al.*, 1984). Crustal aerosol buffering capacity for acidity determined by dissolving samples in deionized water indicates that aerosol buffering capacity increases with increasing Ca<sup>2+</sup> content (Zhao *et al.*, 1985). It is the reason that snow pH correlates positively with Ca<sup>2+</sup> and negatively with SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> (Table 3).

### 3.3. Comparison of ion concentrations in snow between Svalbard and other remote regions

As mentioned before, the snowpit 1–7 from Longyearbyen were accumulated from Autumn to Spring. Only snowpit 8 with depth of 2.2 m may represent more than one-year snow accumulation. Therefore ion concentrations of snowpit 8 are chosen to compare with those from other remote regions. The data of ion concentrations in snowpack from Arctic, Antarctic and Qinghai-Tibetan (Q-T) Plateau are also chosen from more than one-year snow accumulation. In Table 4, all mean values of ion concentrations in snowpack are arithmetical averages and represent multi-year ion concentrations in snow in different sites.

Concentrations of sea-salt species (Na<sup>+</sup>, Cl<sup>-</sup> and Mg<sup>2+</sup>) and SO<sub>4</sub><sup>2-</sup> in Longyearbyen and Ny-Alesund of Svalbard are

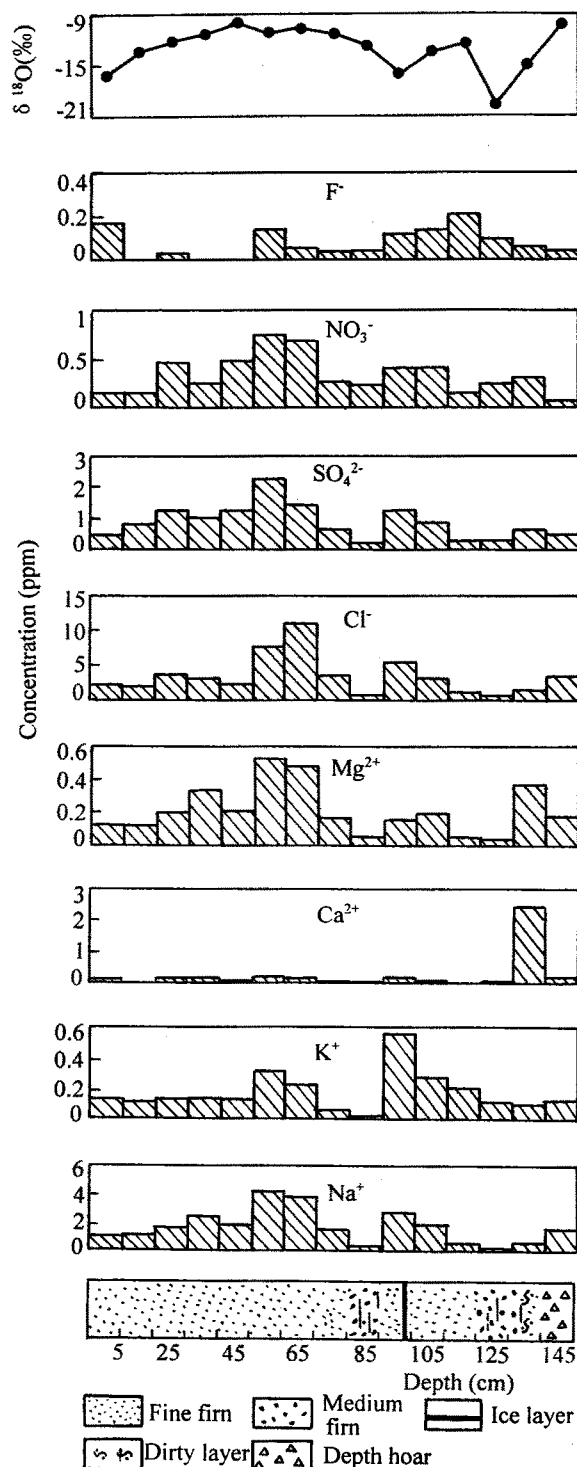


Fig. 2. Concentrations of major ions and δ<sup>18</sup>O in snowpit 7 at Bogenbreen

Table 4 Comparison of ion concentrations in snow between Longyearbyen and other remote regions (units: ppm)

Regions		Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	References
Svalbard	Longyearbyen	1.850	0.928	0.222	0.181	3.282	0.201	0.589	(Pit 8) This paper
	Ny-Alesund	1.873		0.077	0.126		0.080	0.468	Semb et al., (1984)
Central Greenland		0.004	0.002	0.008	0.001	0.017	0.143	0.093	Yang et al., (1996)
Antarctica	South Pole	0.013		0.002	0.001	0.030	0.094	0.039	Qin
	Larsen Ice Shelf	1.054		0.049	0.127	1.872	0.046	0.210	(1995)
Qinghai-Tibetan Plateau	Guliya Ice cap	0.450		1.030	0.150	0.290	0.240	0.310	Li et al., (1995)
	No. 29 Gl.	0.195	0.242	1.879	1.419	0.323	0.154	0.213	Ren (1999)
	Dasuopu Gl.	0.068	0.040	0.169	0.014	0.010	0.179	0.120	Kang et al. (1999)
	Mushitage Gl.	0.100		1.040	0.110	0.150	0.300	0.370	Li <sup>(1)</sup> (1994)
	Zepu Gl.	0.440		0.150	0.530	0.430	0.000	0.150	Yao et al., (1993)

(1) Li Z.Q.(1994):A study on aerosol recorded in glacier in Qinghai-Tibetan Plateau, dissertation of Lanzhou Institute of Glaciology and Geocryology, CAS, 66-73.

similar, while crustal Ca<sup>2+</sup> concentration is much higher in Longyearbyen than that in Ny-Alesund. The lower Ca<sup>2+</sup> concentrations may be due to the local crustal dust covered by snow and ice in Ny-Alesund of the northwestern Spitsbergen (Fig. 1). The lower NO<sub>3</sub><sup>-</sup> concentration in Ny-Alesund than in Longyearbyen needs further studying.

Concentrations of most of the major ions in Longyearbyen region are higher than those in Greenland. For sea-salt species, different transportation distance from the coast to inland between Svalbard and central Greenland may cause the huge difference of ion concentrations. The concentrations of Ca<sup>2+</sup> and K<sup>+</sup> in Longyearbyen are much higher than those in Greenland, where huge ice sheet in central Greenland covers the local source of dust. The concentrations of NO<sub>3</sub><sup>-</sup> in Longyearbyen is slightly higher than that in Greenland. SO<sub>4</sub><sup>2-</sup> in Longyearbyen is much higher than that in Greenland, which could be due to the contribution of sea-salt SO<sub>4</sub><sup>2-</sup> and other sources in Longyearbyen.

Na<sup>+</sup> and Cl<sup>-</sup> concentrations in Longyearbyen are much higher than those in inland of Antarctica and Q-T Plateau, and similar to those in coastal Antarctic (Larsen Ice Shelf) and the margin of Q-T Plateau, where the precipitation are mainly influenced by marine air mass. In Longyearbyen, Ca<sup>2+</sup> concentration is higher than that in Antarctic and central and southern Q-T Plateau, but lower than that in western and northern Q-T Plateau, where there are the vast arid and semi-arid desert regions with plenty of crustal dust influencing snow chemistry (Li et al., 1995; Wake et al., 1993; Kang et al., 1999). In Longyearbyen, NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup> concentrations are roughly same as those in western and northern Q-T Plateau, while higher than those in other regions. NO<sub>3</sub><sup>-</sup> has multiple sources, for example, stratosphere-troposphere interaction, anthropogenic, biologic and volcanic sources (Finkel et al., 1986; Mayewski et al., 1987; Davidson, et al., 1989; Beer et al., 1991). In Longyearbyen, NO<sub>3</sub><sup>-</sup> may reflect the combination of these sources. While in western and northern Q-T Plateau (e.g. Guliya Ice Cap), at least 66% of NO<sub>3</sub><sup>-</sup> comes from dust input in the dust storm season (Li et al., 1995). In Longyearbyen about half of SO<sub>4</sub><sup>2-</sup> comes from sea-salt aerosol, while 76% of SO<sub>4</sub><sup>2-</sup> results from dust influx in the dust storm season in Guliya Ice Cap (Li et al., 1995).

#### 4. Conclusions

(1) Cl<sup>-</sup> and Na<sup>+</sup>, which mainly come from sea-salt aerosol, are the dominant soluble impurities in snowpacks and snowfall in Longyearbyen region, suggesting that the

precipitation is mainly controlled by marine air mass in the region. Ca<sup>2+</sup> mainly comes from local exposed rock and has the highest concentration in snowpack dirty layer.

(2) Snow SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup> and Na<sup>+</sup> all correlate closely and the peak values are consistent in snowpack, though they have different sources. Nss SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> may originate from long-distance transport of mid-latitude anthropogenic pollution. Snow conductivity correlates closely with Na<sup>+</sup>, Cl<sup>-</sup> and Mg<sup>2+</sup> with correlation coefficients ranging from 0.72-0.83. Snow pH correlates positively with Ca<sup>2+</sup> and negatively with SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup>.

(3) The comparison for more than one-year snow chemistry indicate that the concentrations of Na<sup>+</sup> and Cl<sup>-</sup> in snowpacks in Svalbard are higher than those in snowpacks from other remote regions, such as inland of Greenland, Antarctic, and Q-T Plateau. Ca<sup>2+</sup> concentration in Svalbard is higher than that in central Greenland, Antarctic, and the margin of Q-T Plateau; however lower than that in central, northern, and western Q-T Plateau. NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup> concentrations in Svalbard are close to those in the western and northern Q-T Plateau, but higher than those in other regions.

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