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Spatial variations of $\delta^{18}O$ and ion species in the snowpack of the northwestern Greenland ice sheet

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Abstract

To determine the transport processes of water vapor and aerosols over the northwestern Greenland ice sheet, we undertook a glaciological observation at a coastal site on the northwestern part of the ice sheet and revealed spatial variations in $\delta^{18}O$ and in the concentrations of chemical substances in surface snow and the snowpack. On the outlet glacier (the Meehan glacier), water vapor and sea salt were transported from the coast. On the inland ice sheet in northwestern Greenland, water vapor, mineral dust, anthropogenic substances such as NO_3^- and SO_4^{2-}, and $CH_3SO_3^-$ from marine phytoplankton were transported from the west coast of Greenland via the central part of the Greenland ice sheet.

Key words: Greenland ice sheet, snow pack, $\delta^{18}O$, ion species

1. Introduction

The stable isotope composition of precipitation is controlled by variations in the origin of the water and the condensation history during atmospheric transport, and the chemical composition of precipitation is controlled by its source and the history of scavenging processes and chemical reactions during atmospheric transport. Therefore, spatial variations in the stable isotope and chemical composition of surface snow on the Greenland ice sheet can provide valuable information relating to the transport processes of water vapor and aerosols over the Greenland ice sheet.

A significant study of the spatial variability of the snow on the Greenland ice sheet was undertaken by Benson, who reported that the snow deposited by a single storm had a lower O^{18}/O^{16} ratio at higher altitudes (Benson, 1960). Johnsen *et al.* (1989) showed the relationship between the mean $\delta^{18}O$ of snow deposited on the Greenland ice sheet and the annual mean surface temperature, as represented by the temperature at 10- or 20-m depths. Yang *et al.* (1996) reported that Cl^-, Na^+, and Mg^{2+} concentrations decreased and the NO_3^- concentration increased with increasing elevation on the Greenland ice sheet. All of these studies were undertaken at relatively higher sites (>2000-m elevation) on the Greenland ice sheet and considered spatial variations in the chemical properties of snow that resulted from large-scale atmospheric circulation.

We undertook a glaciological observation in 2000 at a coastal site in the northwestern part of the Greenland ice sheet to show the spatial variations in $\delta^{18}O$ and chemical species on the snow pack at a lower elevation site (< 2000 m), where the transportation of water vapor and aerosols was relatively more affected by the regional topographic characteristics than is the case at a higher elevation site.

2. Observation and chemical analysis

The research area was the northern part of the Thule area in northwestern Greenland (Fig. 1). The southwest of Thule area faces Baffin Bay, and the northwest faces the Nares Strait and Ellesmia Island. The expedition base was established in Siorapaluk village, which is located at 77°47′N, 70°45′W and faces Robertson Fjord. Meehan glacier, where a glaciological expedition was undertaken, is located at the east end of Robertson Fjord.

The observation route is indicated in Fig. 1. We started from Siorapaluk village on 17 April 2000, moved across the sea ice to the end of Robertson Fjord, climbed the Meehan glacier, and advanced on the Greenland ice sheet. We arrived at the terminal point of the route (N78°9′43″, W64°44′39″) on 28 April and returned to Siorapaluk on 7 May. The route can be separated into two parts. One was the route from the seacoast

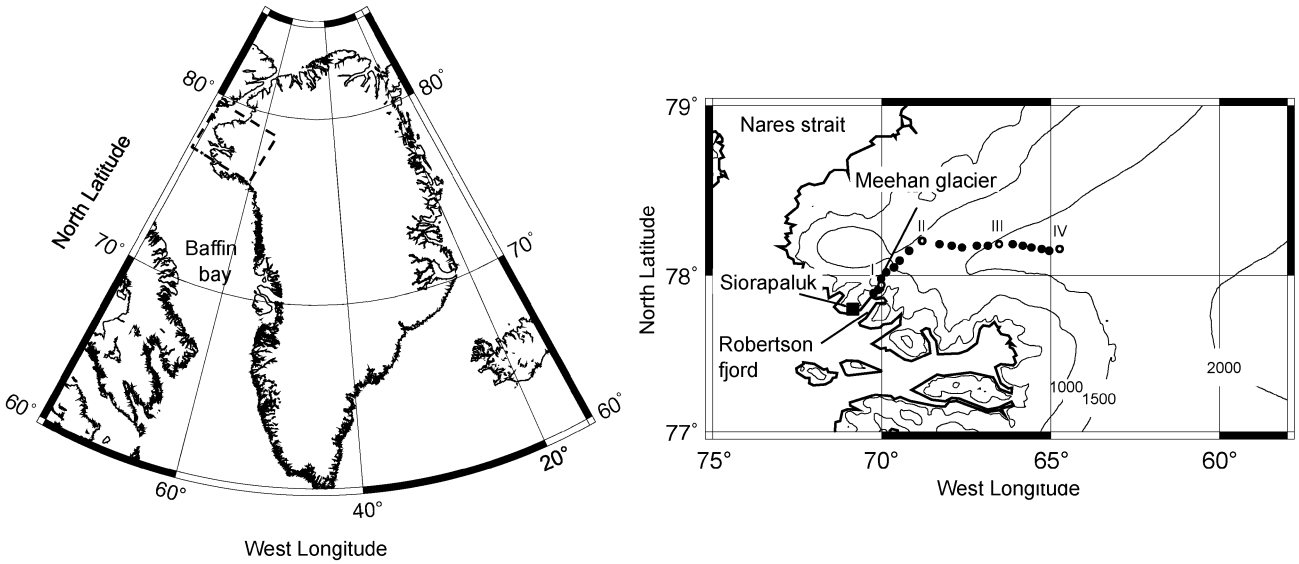

Fig. 1. Location of the study area and the observation sites with snow pits (○; I-IV) and surface snow sampling (●).

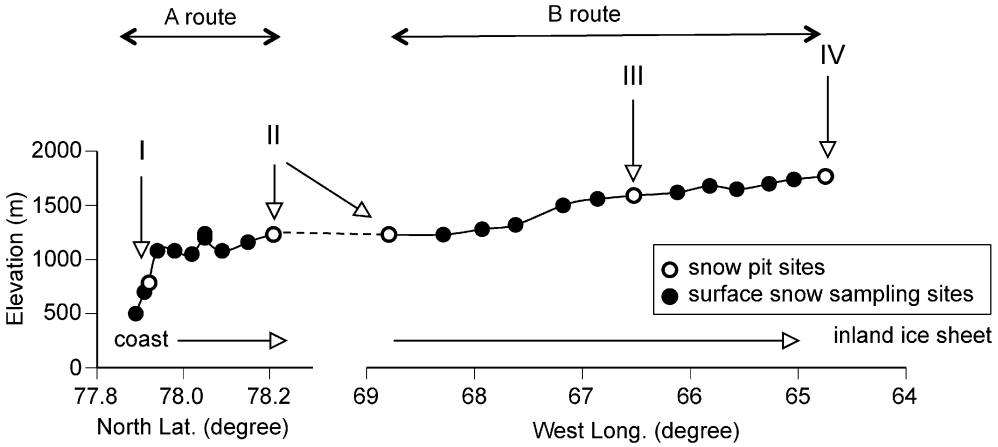

Fig. 2. Elevation and latitude of the observation sites on the A-route, and elevation and longitude of observation sites on the B-route. Snow pit sites and surface snow sampling sites are indicated by white circles (○) and black circles (●), respectively. Pit II site is at the boundary between the A-route and the B-route, and indicated in both the A-route and the B-route.

northward along Meehan glacier (A-route). The second was the route from the top of Meehan glacier eastward on the inland ice sheet (B-route) (Fig. 2). We conducted snow pit observations at four sites on the route to measure stratigraphy, grain size, snow temperature, and density. Snow samples for chemical analysis were also collected from snow pit walls using a stainless steel tool to transfer snow into polyethylene bags. Surface snow samples for chemical analysis were also collected at 19 sites on the route using a stainless steel tool and placed in polyethylene bags. The locations and elevations of the sites of the snow pits and surface snow samplings are shown in Fig. 2. The snow samples were kept frozen and were transported to Siorapaluk. The snow samples were melted at ambient temperature and then transferred into 100-mL polypropylene bottles. All equipment and bottles were previously cleaned by ultrapure water in an ultrasonic bath. The liquid samples were then transported to the National Institute of Polar Research, Japan, frozen in a cold room (−20℃), and kept frozen until the chemical analyses were performed.

The concentrations of cation species (Na^+, K^+, Mg^{2+}, Ca^{2+}) and anion species ($CH_3SO_3^-$, Cl^-, NO_3^-, SO_4^{2-}) in the snow samples were determined by ion chromatography (model 500x, Dionex). Oxygen isotopes were measured with a mass spectrometer (model δE, Finnigan MAT). All analyses were performed at the National Institute of Polar Research, Japan.

3. Results and Discussions

3.1 Spatial variation in $\delta^{18}O$ in surface snow

Fig. 3a shows the spatial variation in $\delta^{18}O$ in surface snow. On the A-route, $\delta^{18}O$ decreased remarkably with the latitudes of sampling sites, which are roughly corresponding to the elevations of the sites (Fig. 2). This trend is consistent with the relationship between $\delta^{18}O$ in

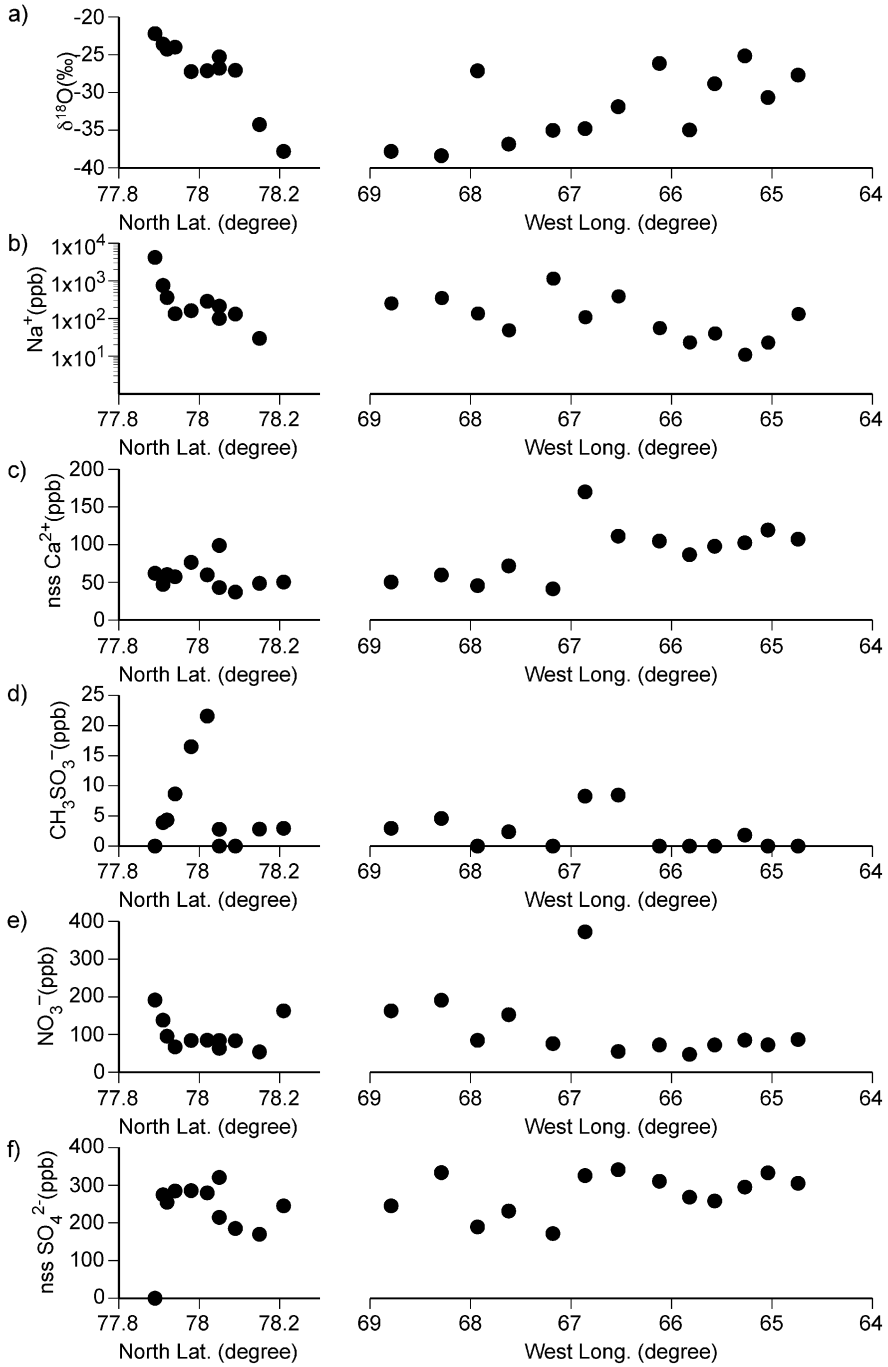

Fig. 3. Spatial variations in (a) $\delta^{18}O$, (b) Na^+, (c) non-sea salt Ca^{2+}, (d) $CH_3SO_3^-$, (e) NO_3^-, and (f) non-sea salt SO_4^{2-} in surface snow. Concentration of Na^+ is shown on a logarithm scale.

snow and elevation, which indicates lower $\delta^{18}O$ observed at higher elevations (*e.g.*, Epstein and Langway, 1959; Dansgaard, 1961). On the B-route on the Greenland ice sheet, $\delta^{18}O$ increased with the longitude of sampling sites corresponding to the elevation (Fig 2), which was not consistent with results reported for the inland ice sheet by Benson (1960), where $\delta^{18}O$ in precipitation decreased with elevation. Fig. 4a shows vertical profiles of $\delta^{18}O$ in the snowpack from snow pit observations (sites I–IV). All profiles of $\delta^{18}O$ showed clear variations, which may correspond to seasonal cycles. The values of $\delta^{18}O$ at Site I, which is coastal site, was higher than at Site II. On the B-route, the values of $\delta^{18}O$ at site IV, an ice sheet in the interior, was higher than those at sites III and II (IV＞III ＞II). These trends of spatial variation of $\delta^{18}O$ on snow pit observation were similar to those in the surface snow.

3.2 Spatial variations in chemical species in surface snow

Fig. 3b–f show the spatial variations in the concentrations of Na^+, non-sea salt (nss) Ca^{2+}, $CH_3SO_3^-$, NO_3^-, and nss SO_4^{2-} in surface snow along the observation route. The concentrations of nss Ca^{2+} and nss SO_4^{2-} were calculated using the ratio of Ca^{2+} and SO_4^{2-} to Na^+ in bulk seawater, respectively. The concentration of Na^+, which mainly originates from sea salt aerosol in polar regions, decreased remarkably with

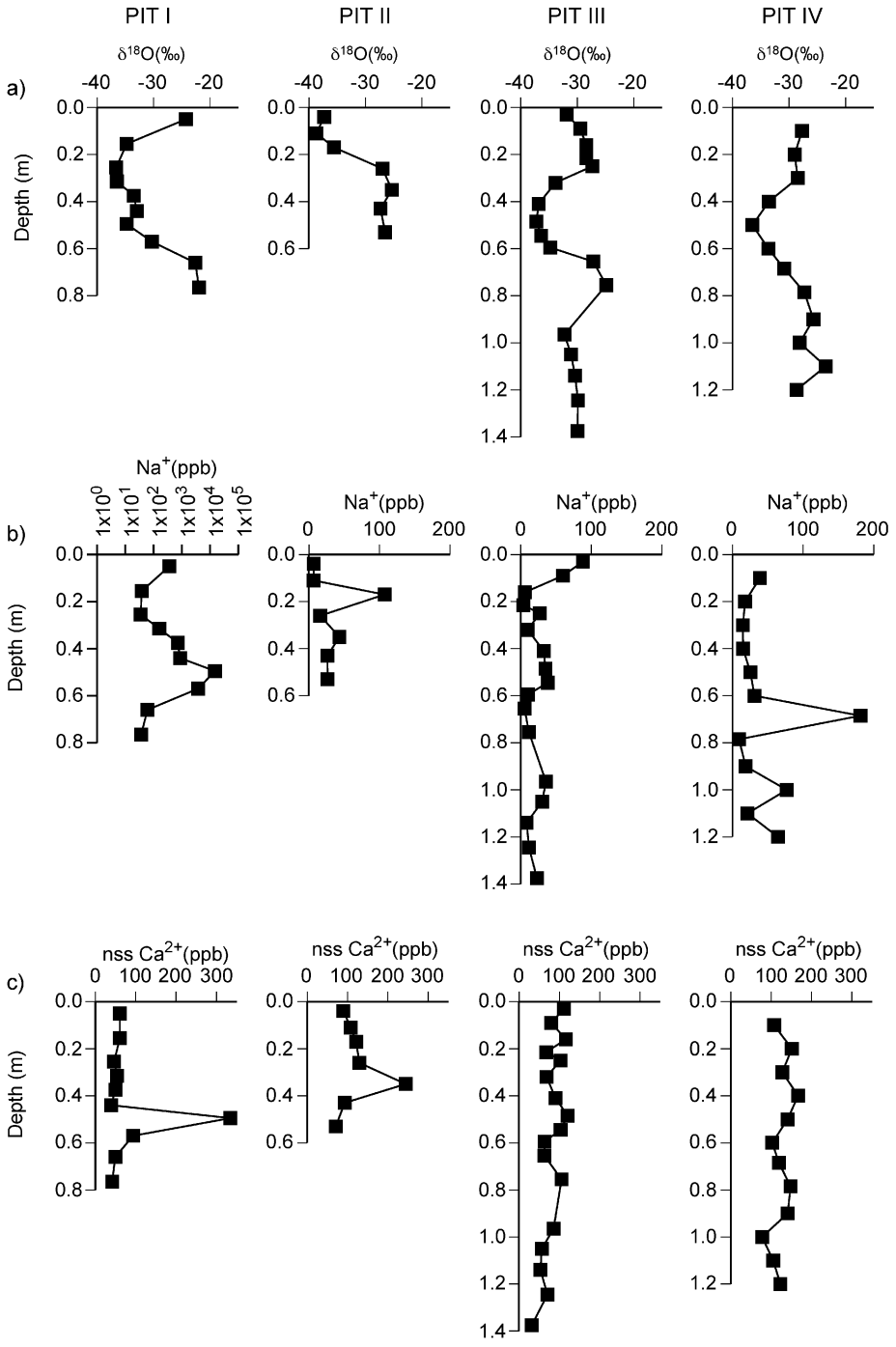

Fig. 4. Vertical profiles of (a) $\delta^{18}O$, (b) Na^+, (c) non-sea salt Ca^{2+}, (d) $CH_3SO_3^-$, (e) NO_3^-, and (f) non-sea salt SO_4^{2-} of snow pit observations. Concentration of Na^+ of PIT I is shown on a logarithm scale.

distance from the seacoast on the A-route and did not vary on the B-route. The concentration of nss Ca^{2+}, which mainly originates from terrestrial mineral dust, did not vary on the A-route, and exhibited a relatively higher concentration in the inland part of the ice sheet (<67° west longitude) on the B-route. $CH_3SO_3^-$, which is emitted by marine phytoplankton activity, increased with elevation only on the lower part of the A-route. On the higher part of the A-route and on the B-route, the concentration of $CH_3SO_3^-$ was low and did not vary. NO_3^-, which mainly originates from fossil fuel combustion and biomass burning, and nss SO_4^{2-}, which mainly originates from fossil fuel combustion and volcanic gases, did not display significant spatial variations on either the A- or B-route. Fig. 4b–f show the vertical profiles of Na^+, nss Ca^{2+}, $CH_3SO_3^-$, NO_3^-, and nss SO_4^{2-} of the snowpack from snow pit observations (sites I–IV). The Na^+ concentration at site I, which is a coastal site, was remarkably higher than that at the other sites. The nss Ca^{2+} concentrations on the A-route were low, except for peaks at 0.5 m at site I and at 0.35 m at site II. On the B-route the concentration of nss Ca^{2+} at site IV, an ice sheet in the interior, was higher than that at site III. This trend was similar to the spatial trend of nss Ca^{2+} in

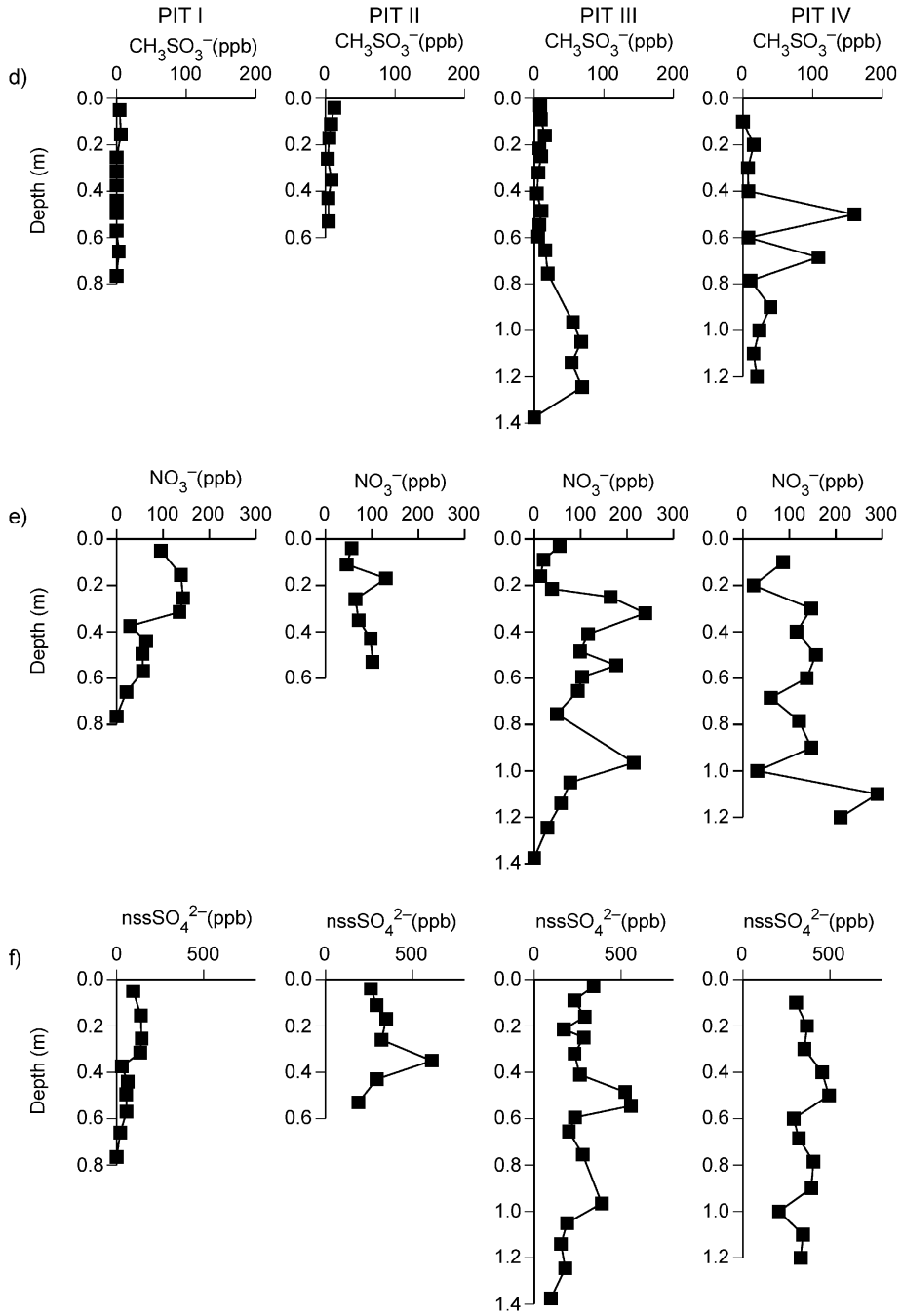

Fig. 4. Continued.

surface snow. Concentrations of $CH_3SO_3^-$ at the bottom of the snow pit in sites III and IV were much higher than that in the surface snow. The high content of $CH_3SO_3^-$ may have originated from marine phytoplankton activity in the previous spring and summer. The concentrations of NO_3^- and nss SO_4^{2-} generally increased with the elevation of snow pit sites.

4. Summary

From the spatial variations in $\delta^{18}O$ and chemical species in the surface snow and snow pit samples, we suggest that the airborne transportation of water vapor and chemical substances over the northwestern Greenland ice sheet occurs as follows. On the outlet glacier (Meehan glacier), water vapor and sea salt are transported from the coast, and on the inland ice sheet in northwestern Greenland, water vapor, terrestrial substances such as mineral dust, anthropogenic substances such as NO_3^- and SO_4^{2-}, and $CH_3SO_3^-$ from marine phytoplankton are transported from the west coast of Greenland via the central part of the Greenland ice sheet. Ohmura and Reeh (1991) showed the wind streamlines over the Greenland ice sheet. In both summer and winter, streamlines in the vicinity of the B-route are modified by the Baffin Bay low. On the west coast of Greenland, the air mass south of Baffin Bay is initially moves toward the northeast and then turns

northwest at 75°N, 50°W. Therefore, the B-route in this study receives southeast wind with water vapor and chemical substances originating from the south of Baffin Bay. Generally, $\delta^{18}O$ of aged water vapor tends to be lower due to the ease of scavenging of heavier water molecules during transport; similarly, the concentrations of chemical substances in aged aerosols tend to be lower due to the scavenging processes that occur during transport. Consequently, the spatial variations in $\delta^{18}O$ and chemical substances on the B-route support the streamlines estimated by Ohmura and Reeh (1991).

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References

Benson, C. S. (1960): Stratigraphic studies in the snow and firn of the Greenland Ice Sheet. Ph.D. thesis, California Institute of Technology.

Dansgaard, W. (1961): The isotopic composition of natural waters. *Medd. Om Grønland 165*, **No 2**, 120 pp.

Epstein, S. and Langway, C. C., (1959): Oxygen isotope studies. *Trans. Am. Geophys. Union*, **40**, 81–84.

Johnsen, S. J., Dansgaard, W. and White, J. W. C. (1989): The origin of Arctic precipitation under present and glacial conditions. *Tellus*, **41B**, 452–468, doi: 10.1111/j.1600–0889.1989.tb00321.x.

Ohmura, A. and Reeh, N. (1991): New precipitation and accumulation maps for Greenland. *J. Glaciol.*, **37 (125)**, 140–148.

Yang, Q., Mayewski, P. A., Linder, E., Whitlow, S. and Twickler, M. (1996): Chemical species spatial distribution and relationship to elevation and snow accumulation rate over the Greenland Ice Sheet. *J. Geophys. Res.*, **101 (D13)**, 18629–18637, doi: 10.1029/96JD01061.