



Seasonal variations in the major chemical species of snow at the South East Dome in Greenland



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ABSTRACT

We analyze snow-pit samples collected in May 2015 at the South East Dome (SE Dome) on the Greenland ice sheet. The analysis includes high-resolution records of δD and $\delta^{18}O$, as well as the major ions, $CH_3SO_3^-$, Cl^- , NO_3^- , SO_4^{2-} , Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+} . We find that the 3.55-m snow pit recorded temperature and aerosol proxies back to summer or autumn of 2014. This indicates a higher accumulation rate than those at other major drilling sites in Greenland. Due to this high accumulation rate, ion concentrations except Na^+ are lower than those typical of the central Greenland ice sheet. Concerning seasonal variability, the Na^+ , Cl^- , Ca^{2+} , Mg^{2+} , and NO_3^- vary similarly to other sites in Greenland, with the Na^+ and Cl^- peaking in winter to early spring, Ca^{2+} peaking in spring, Mg^{2+} peaking in winter to spring, and NO_3^- towards a peak in summer while showing smaller peaks in winter to spring. The NH_4^+ increased in spring, and SO_4^{2-} increased in autumn to winter at SE Dome. On the other hand, the seasonal trend in the Cl^-/Na^+ ratio differs from those in the inland region. As we did not fully recover one seasonal cycle, some seasonal peaks may have been missed.

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1. Introduction

Polar ice preserves a record of past atmospheric composition in the form of important proxies for reconstructing past atmospheric environmental conditions. For example, paleoclimate records going back more than 100,000 years have been reconstructed from the Greenland deep ice cores, including those from Camp Century (Hansen and Langway, 1966), Renland (Hansson, 1994), GRIP (Dansgaard et al., 1993), GISP2 (Grootes et al., 1993), North GRIP (NGRIP members, 2004), and NEEM (NEEM community members, 2013).

In May 2015, to reconstruct Greenland's past atmospheric environment with super-high resolution, we drilled a shallow ice core and observed the snow at the ice divides (Bamber et al., 2000) in the southeast part of the Greenland ice sheet, South East Dome; SE Dome (Iizuka et al., 2016) (Fig. 1). This area is upstream of three major outlet glaciers (Helheim, Fenris, and Midgård Glaciers) in the

Sermilik Fjord catchment (Mernild et al., 2010). Here, the surface elevation exceeds 3000 m, with the ice thickness exceeding 1000 m (Bamber and Layberry, 2011; Bamber et al., 2013). The distance from the nearest coast is only about 120 km – much closer than other deep-ice drilling sites such as GRIP, GISP2, NGRIP, and NEEM. The present annual mean temperature around this region is approximately -20 to -25 °C (Fausto et al., 2009). At the nearby Das2 site, just 40-km north of SE Dome, the average annual accumulation rate from 1936 to 2002 is 0.90 ± 0.19 m ice yr^{-1} (Pedro et al., 2012). This is about 3–4 times larger than that in the central Greenland ice sheet (Vinther et al., 2010) and 35 times larger than that in the inland Antarctic ice sheet, Dome Fuji (Watanabe et al., 2003). Thus, at the SE Dome, the annual mean temperature is relatively low, the annual accumulation rate relatively high. This implies that the chemical composition is relatively unaffected by melting in summer, and by post-depositional processes. Thus, we can expect to reconstruct past environmental proxies with high reliability and with very high resolution from the SE Dome ice core.

The seasonal variability of snow chemistry has been investigated at various sites on the Greenland ice sheet including Dye3 (Beer et al., 1991), Summit (Whitlow et al., 1992; Legrand and

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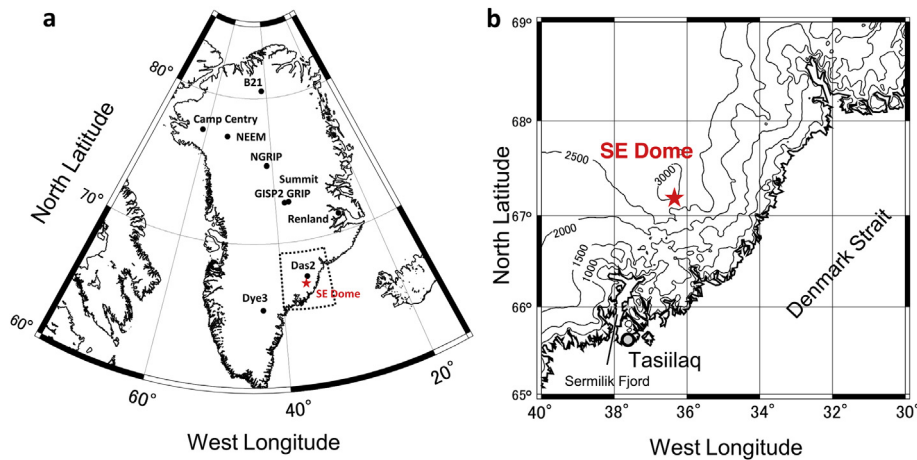


Fig. 1. Location of the study area and observation site. Black dots are other sites mentioned in the text. Elevation data is from ETOPO1 (Amante and Eakins, 2009).

Mayewski, 1997; Dibb et al., 2007), B21 (Fischer, 2001) and NEEM (Kuramoto et al., 2011; Gfeller et al., 2014) (Fig. 1a). These studies, covering a wide range of locations, show clear and similar seasonal variabilities for the stable water isotope ratios ($\delta^{18}\text{O}$ and δD) and chemical components. For example, Steffensen (1985) reports that the $\delta^{18}\text{O}$ value of snow correlates with the temperature at Dye3. A similar seasonality in $\delta^{18}\text{O}$ exists at other Greenland sites (Finkel et al., 1986; Beer et al., 1991; Legrand and Mayewski, 1997; Kuramoto et al., 2011). Concerning the dust and chemical components, dust and Ca^{2+} are of terrestrial origin and peak in late winter to spring (Whitlow et al., 1992; Legrand and Mayewski, 1997; Kuramoto et al., 2011), whereas the Na^+ and Cl^- originate from sea-salt, peaking in winter to early spring (e.g., Beer et al., 1991; Whitlow et al., 1992; Davidson et al., 1993; Kuramoto et al., 2011; Gfeller et al., 2014). The NH_4^+ originates mainly from bacterial decomposition and biomass burning and has similar seasonality over much of the Greenland ice sheet, peaking in the summer (Whitlow et al., 1992; Bergin et al., 1995; Fuhrer et al., 1996; Legrand and Mayewski, 1997; Kuramoto et al., 2011).

The NO_3^- and SO_4^{2-} have both natural and anthropogenic sources. The natural source of NO_3^- is from bacterial decomposition in soils, biomass burning, and lightning, producing a strong peak in summer (e.g., Fuhrer et al., 1996; Silvente and Legrand, 1993; Hansson and Holmén, 2001; Fischer et al., 2015). The anthropogenic NO_3^- is from various activities such as fossil-fuel combustion, peaking in winter to early spring (Finkel et al., 1986). Apart from volcanism, the natural source of SO_4^{2-} is DMS emission from marine biogenic activity and continental biogenic emissions, both of which peak in summer (Kuramoto et al., 2011). The anthropogenic source of SO_4^{2-} is from various activities as well as NO_3^- , peaking in winter to early spring (Beer et al., 1991; Kuramoto et al., 2011). However, from year to year and from site to site, the SO_4^{2-} and NO_3^- peaks appear in a different manner. For example, the SO_4^{2-} peak appeared in spring to summer at Summit in 1983–1990 (Legrand and Mayewski, 1997) and in spring and autumn at Dye3 in 1977–1983 (Beer et al., 1991), whereas they appear in winter to spring at Summit in 1997–2002 and at NEEM in 2009 (Dibb et al., 2007; Kuramoto et al., 2011).

In addition to each component's seasonality, the overall chemical composition of impurities in snow and ice helps to understand the atmospheric environment (e.g., Oyabu et al., 2014, 2015). Analyzing the ionic balance and chemical compositions of impurities may provide clues for understanding the impurity sources and chemical processes during transportation and after deposition.

For example, in the inland Greenland ice sheet (e.g., Summit and NEEM), ice from glacial times is more alkaline than that from the present because of its higher dust (CaCO_3) concentration (Legrand and Mayewski, 1997; Oyabu et al., 2015). The more recent ice is more acidic than pre-industrial ice because human activities, notably fossil-fuel burning, have significantly increased the level of several acidic species (NO_3^- , SO_4^{2-} , and to a lesser extent F^- , Cl^- , and the light carboxylates) in Greenland snow deposited since 1940 (Legrand and Mayewski, 1997).

In central Greenland, the chemical components of snow and ice have been well studied. However, the southeastern part of the Greenland ice sheet has not been investigated, except for accumulation rate and ^{10}Be of the Das2 ice core by Pedro et al. (2012). Thus, the SE Dome region is a blank area in terms of snow and ice chemistry. To accurately interpret the chemistry data and for dating the SE Dome ice core, one should understand this region's present-day seasonal variations and characteristics of the chemical components. Here we investigate the variability of stable water isotopes and chemical components of the snow at the SE Dome.

2. Observation and chemical analysis

The research area is at the South East Dome (SE Dome) ($\text{N}67^\circ 11'$, $\text{W}36^\circ 22'$; 3170 m a.s.l.), in the southeast part of the Greenland ice sheet (Fig. 1). We ran our snow-pit observations on the 26 and 27th of May in 2015. A 3.55-m-deep pit was dug from the surface on the windward side of the campsite at where thought to have the least possibility of being influenced by the camp. After observing the snow layers, we measured the snow densities and temperatures, as well as collecting a sample, at every 0.05-m depth increment. The snow sample was collected using a clean stainless snow sampler, and put into polyethylene bag (Nasco Whirl-Pak). They were then melted in the polyethylene bags at room temperature, and transferred to clean polypropylene bottles in doors in Tasilaq village. The samples were brought to the Institute of Low Temperature Science (ILTS), Hokkaido University, Japan, and then stored in a refrigerator. The ion concentrations of CH_3SO_3^- , Cl^- , SO_4^{2-} , NO_3^- , Na^+ , Ca^{2+} , NH_4^+ , Mg^{2+} , and K^+ were then measured by ion chromatography (Thermo Scientific ICS-2100; for the cation, column is Dionex CS-12A and eluent is 20 mM MSA; for the anion, column is Dionex AS-14A and eluent is 23 mM NaOH). The stable water isotope ratio was measured by a water-isotope analyzer (Picarro; L2120-i/L1102-i) at the ILTS. Analytical precision is below 10% for ion concentration, ± 0.6 – 1.0‰ for δD and ± 0.08 – 0.1‰ for $\delta^{18}\text{O}$.

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