Glaciological and meteorological observations at the SE-Dome site, southeastern Greenland Ice Sheet

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Abstract

In order to understand 1) temporal variations of anthropogenic aerosols from European regions under the Icelandic low with high time resolution, and 2) the snow densification mechanism at the high accumulation dome in Greenland, we drilled a 90.45 m ice core in a high accumulation area of the southeastern Greenland Ice Sheet. The drilling site (SE-Dome; 67.18°N, 36.37°W, 3170 m a.s.l.) is located 185 km north of the town of Tasiilaq in southeastern Greenland. We also conducted borehole temperature measurements. The temperature in the borehole was −20.9°C at a depth of 20 m. In addition, we did snow-pit observations, aerosol sampling, snow sampling for chemical and physical analyses and meteorological observation. Air temperature and air pressure were on average −16.8°C and 667 hPa during our stay. The aerosol concentration in the top surface 0.1 m snow at SE-Dome in the spring of 2015 was lower than those of the other regions in Greenland, likely due to a highland dome of the ice sheet and/or dilution of mass flux by high snow accumulation.

Key words: Greenland Ice Sheet, ice core, Tasiilaq, snow chemistry, SE-Dome

1. Introduction

Polar ice sheets are good archives of paleo-environmental events. The highland region of ice sheets preserves paleo-environmental proxies from a wide-area around the region. In particular, domes in ice sheets are good locations for precise reconstruction of paleo-environmental events. Therefore, many ice cores have been drilled from ice sheet domes such as Dome Fuji (Watanabe et al., 2003), EPICA Dome C (EPICA community members, 2006), EPICA Dome C (EPICA community members, 2004), GRIP (Greenland Ice-core Project Members, 1993), GISP2 (Grootes et al., 1993), and NGRIP (North Greenland Ice Core Project Members, 2004). General characteristics of the dome cores in ice sheets are: 1) low accumulation rate due to being an inland dry area, and 2) low temperature due to highland in polar region. Ice cores in areas with low accumulation rates and low temperatures allows us to reconstruct past environments up to several hundred thousand years old with high quality measurements, in the regions that have experienced less melting. However, ice cores in areas with low accumulation rates have the disadvantage of low temporal resolution for the purpose of environmental reconstruction, and occasionally lack seasonal or annual events (Kameda et al., 2008).

Present-day polar ice sheets are located in Antarctica and Greenland. The Greenland Ice Sheet is a better archive of anthropogenic events for the past 150 years than Antarctic Ice Sheet. The primary anthropogenic aerosol compositions are sulfate, nitrate, organic, and black (blown) carbons (IPCC, 2013). These aerosols are likely preserved in the ice sheet with highly regional effects (e.g. Fischer et al., 1998), as northwest Greenland is strongly affected by circumpolar westerlies. In contrast, southeast Greenland is strongly affected by the Icelandic low and the Atlantic Ocean (Buchardt et al., 2012). Ice cores in northwest Greenland preserve anthropogenic aerosols from regions in Asia, including China (Bory et al., 2014). In contrast, ice cores in the southeast Greenland preserve anthropogenic aerosols from Europe, namely post-Industrial Revolution (McConnell et al., 2008). Additionally, climatic changes on the decadal scale, such as Arctic Oscillation and North Atlantic Oscillation, enhance the regional climate, air temperature and precipitation. So, environmental reconstructions from multiple shallow ice cores were performed in Greenland by United States
PARCA project) and German (NGT project) teams (McConnell et al., 2006). However, there remain a few domes in Greenland have been not drilled, and regional climates of the domes have not been reconstructed.

Our team performed an expedition and conducted ice-core drilling at a site in southeast Greenland with one of the highest accumulation domes in Greenland, in a seldom-drilled area, in order to 1) reconstruct anthropogenic aerosols from Europe under the Icelandic low with high time resolution, and 2) make the snow densification mechanism clear at high accumulation dome in Greenland. The drilling site and base town are frontiers for Japanese glaciological expedition. In this paper we report the logistics and aims of the expedition, which was the first ice-core drilling performed by a Japanese team, as well as report our glaciological and meteorological observations.

2. Research Area

The observation site (67.18°N, 36.37°W, 3170 m a.s.l), referred to as SE-Dome, is located 185 km north of the town of Tasilaq in southeastern Greenland. The main Greenland ice divide has a fork at the southern Summit (GRIP/GISP2). In the southern area of the fork, the two ice divides extend southwest to near Narsarsuaq through Dye 3, and extend southeast to near Tasilaq. Likely due to the presence of a high mountain under the ice sheet (Bamber et al., 2013) and high snow accumulation (Burgess et al., 2010), the SE-Dome area forms a dome more than 3,000 m above sea level (Fig. 1). The SE-Dome lies in the upstream section of the Fenris and MIDård Glaciers, which discharge into Sermilik Fjord. The SE-Dome lies headstream of the Helheim Glacier, which is
reported to be the major ice-loss glacier in Greenland (Andresen et al., 2012). The town of Tasilaq was the base for this expedition; details are described in section 4.

Precipitation characteristics of Tasilaq are quite different from the other towns, according to measurements made by the Danish Meteorological Institute (Fig. 2). The main difference is a huge precipitation amount and winter weighting precipitation. These characteristics are likely due to climate condition and water vapor transportation. The climate in southeastern Greenland is controlled by the Icelandic low and precipitation originates from the North Atlantic Ocean (Pedro et al., 2012). The SE-Dome likely has precipitation features similar to Tasilaq. The Icelandic low transports water vapor and aerosols eastward, which indicates that this region is a favorable location to investigate and reconstruct aerosols from Europe, including anthropogenic materials. Since the SE-Dome is located more than 3,000 m above sea level, the precipitation around the SE-Dome is snow almost though a year.

Some modelling and satellite analyses have studied characteristics of the SE-Dome area (Bales et al., 2009; Burgess et al., 2010; Hall et al., 2013; Howat et al., 2014; Helm et al., 2014). These studies characterize the SE Dome areas as having: 1) one of the highlands in Greenland that is more than 3,000 m above sea level; 2) relatively cold air temperatures below −20°C is the annual average, compared to same latitude (67°N) area in Greenland; 3) it is one of the domes in Greenland with the most accumulation (from 0.6 to 0.8 m in water equivalent). An ice core originating from the SE-Dome will have an advantage of coming from the highest accumulation dome in Greenland and be of high quality due to the cold temperatures. These advantages provide us with the potential to reconstruct anthropogenic aerosols from European regions beneath the Icelandic low with high time resolution.

At the site about 30 km north of the SE-Dome, an ice core has been drilled in 2002. The core hereafter referred to as the DAS2 core. The DAS2 core (67.5°N, 36.1°W) reports annual accumulation during the years from 1936 to 2002 was about 0.9 m (Pedro et al., 2012), and also gave measurements for the winter sea salt maximum (oceanic materials), and spring maximum of carbonate and aluminous (terrestrial materials) (Banta et al., 2008). However, anthropogenic aerosol compositions, including sulfate, nitrate, organic and black (brown) carbons, have not been studied.

3. Participants

The project participants included:
Dr. Sumito Matoba (Institute of Low Temperature Science, Hokkaido Univ.), Leader and chief driller,
Dr. Yoshinori Iizuka (Institute of Low Temperature Science, Hokkaido Univ.), Chief of Logistics, driller, and snow pit observation,
Mr. Tetsuhide Yamasaki (Avqngnaq), Logistics and risk management,
Dr. Ikumi Oyabu (Institute of Low Temperature Science, Hokkaido Univ.), driller, snow pit observation and aerosol sampling.
Ms. Moe Kadota (Hokkaido Univ.), ice-core processing.

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Tasilaq</th>
<th>SE-Dome</th>
<th>Drilling</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-May</td>
<td></td>
<td></td>
<td>Preparation of food, fuel and equipment</td>
<td>Set up a drilling system</td>
<td>Meteorological observation</td>
</tr>
<tr>
<td>11-May</td>
<td></td>
<td>4 persons from Reykjavik</td>
<td>Postponed flight because of bad weather and flight schedule</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-May</td>
<td></td>
<td>1 person from Nuuk</td>
<td>Postponed flight because of bad weather and flight schedule</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-May</td>
<td></td>
<td></td>
<td>3 personnel and equipment transported by 1 Bell 212 flight</td>
<td>Stacking in heavy blizzard</td>
<td></td>
</tr>
<tr>
<td>21-May</td>
<td></td>
<td></td>
<td>2 personnel and equipment transported by 1 flight</td>
<td>Drilling</td>
<td></td>
</tr>
<tr>
<td>22-May</td>
<td></td>
<td></td>
<td></td>
<td>Closing drill camp</td>
<td></td>
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<td>26-May</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>27-May</td>
<td></td>
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<tr>
<td>2-Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-Jun</td>
<td></td>
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<td>6-Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Itinerary of this project.
4. Itinerary

The itinerary is summarized in Table 1. Our team chartered a Bell 212 Twin Huey (Bell, United States) helicopter from Air Greenland in Tasilaq, Greenland, and flew personnel and equipment from Tasilaq to the observation site. Total weight of the equipment was approximately 700 kg, volume of gasoline for the generator was 180 L, and volume of kerosene for cooking was 80 L. On May 18 2015, three personnel, the drill system, fuel, food, and sleeping tents were flown to the observation site. We set up two sleeping tents and a drill tent on May 18 (Fig. 3A). However, a heavy storm blew from the night of May 18 through May 20, and the drill tent was broken by strong wind. On May 21, we were able to re-set up a drill tent and built a drill system in the drill tent. On the evening of May 21, two personnel, equipment and food were flown from Tasilaq to the observation site. All scheduled field studies were completed by May 27. However, it was necessary to wait for pick-up flights until June 2 as a result of bad weather. On June 2, all personnel, equipment, part of the ice core and snow samples were flown from the observation site to Tasilaq. An additional pick-up flight was conducted on June 4 to recover the remaining ice cores, samples and equipment. The ice cores were temporarily stored in a freezer below −20°C at the Pilersuisoq general store in Tasilaq. The ice cores were then transported by a 20 ft reeler on HEUNG-A AKITA 0013 vessel from Tasilaq via Aalborg, Denmark and Ishikari, Japan to the Institute of Low Temperature Science at Hokkaido University on August 24. We have confirmed that all ice cores are of high quality and were undamaged during transit. During transit, the ice cores were kept below −25°C by Blue Water Shipping A/S (Denmark) with an agency of GES JAPAN CO., LTD.

Table 2. Progression of the drilling operation. The pitch of shoe means a blade depth every cutting ring.

<table>
<thead>
<tr>
<th>Date</th>
<th>Run No.</th>
<th>Depth (m)</th>
<th>Pitch of Shoe (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
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<td>20</td>
<td>2</td>
<td>6.64</td>
<td>6</td>
<td>Separator</td>
</tr>
<tr>
<td>23-May</td>
<td>42</td>
<td>16.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24-May</td>
<td>83</td>
<td>42.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-May</td>
<td>133</td>
<td>62.05</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>141</td>
<td>151</td>
<td>65.65</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>26-May</td>
<td>161</td>
<td>70.30</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>27-May</td>
<td>193</td>
<td>75.02</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>195</td>
<td></td>
<td>89.95</td>
<td>5</td>
<td>Kink of wire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90.45</td>
<td>5</td>
<td>Breaking of electric wire</td>
</tr>
</tbody>
</table>
5. Field activities

5.1 Ice-core drilling and borehole temperature measurement

After establishing a drilling tent and drilling facilities, we began ice core drilling on the morning of May 22 and completed drilling on May 27 (Fig. 3B). We used a lightweight electromechanical ice-core drilling system developed for use at high elevation by the technical division of the Institute of Low Temperature Science at Hokkaido University (Shiraiwa et al., 2003; Matoba et al., 2014). The total weight of the drilling system was approximately 100 kg. The drill had no jacket and three pantographic type anti-torques, a half-round pulley on the top of the mast. A core barrel was separated into two parts as a chip chamber and core storage space because shortening the length of parts of drill system made for ease of carrying. A drill mast was used as the carrying case of the core barrel. We used two generators (a HONDA model EU16i and a YAMAHA model EF2300i) with a four-cycle, single-cylinder gasoline engine for the drilling operations. For high-elevation use, we replaced the fuel spray nozzle in the carburetor with one with a smaller hole. On May 27, we finished drilling the ice core at a depth of 90.45 m, after 195 completed drilling runs. The average length of ice cores was 0.479 m. The drilling operation is summarized in Table 2. It took a total of 54.95 hours to drill down to 90.45 m (Fig. 4). The production rate was 1.65 m h⁻¹. We conducted stratigraphic observations of the ice core, and recorded the stratigraphic features and lengths of the ice core over the entire depth of the core. The ice core contains few ice layers, whose thicknesses are almost less than 0.02 m. In the field, ice cores were stored in insulting boxes, and transported to the freezer in Tasilaq by a helicopter on June 2 and 4.

We measured the ice temperature of the borehole wall on May 26 after completion of the ice-core drilling. The ice temperature was measured with a thermometer with a thermistor sensor (Techno-seven model BYE-64 T and D corporation model TR-52). The resistance of the sensor was measured using a digital multimeter at a resolution of 10 ohms with a precision of 0.1 °C. The room temperature near the drill winch in the drill tent just before the borehole measurement was −15.2 °C. The sensor was inserted into the borehole and left for 25 min at the 20 m depth. The temperature at 20 m depth was −20.9 °C.

5.2 Aerosol, precipitation and surface snow sampling

Aerosol, precipitation, surface snow sampling, and snow pit observation were performed at 150 m windward (northeastward) point from the drilling site. Aerosols were sampled using the filtering method. A stake of 3 m length was run through the snowpack, and single filter pack was fixed on the stake at a height of 1.5 m. The air going through the filter pack was aspirated at a rate of 2.0-3.0 L min⁻¹ by a diaphragm pump (SIBATA MP-Σ 500N). A polycarbonate filter was used with a pore size of 0.45 μm (Advantec, K040.A025A). We collected aerosols in four periods: 1) 1200 to 1800 on May 26; 2) 800 to 1650 on May 27; 3) 640 to 1230 on May 28; and 4) 1400 to 1900 on May 29. After sampling, the filter pack was sealed in a clean plastic bag. The bags were transported in a frozen state, together with the ice core.

For precipitation sampling, snow was collected in a polyethylene bag fitted on an approximately 40 L carton. Precipitation was collected twice: 1) at 7:00 on May 24; and 2) at 8:00 on May 27. After collection, the snow was transferred to a polypropylene bottle, and the bottles were transported in a frozen state, together with the ice core.

On May 27, we sampled surface snow for analyses of black carbon (BC), organic carbon (OC), and dust concentrations at 150 m north of the drilling site. We obtained two samples. One from surface 0.02 m in depth; the second from 0.02-0.10 m in depth. We collected 2 kg of surface snow per sample in a dust free pack. After sealing the pack, the samples were transported in a frozen state, together with the ice core.

Also on May 27, we concreted surface snow using 1-Bromododecane (B0587; Tokyo Chemical Industry Co., Ltd.) in order to fix the snow structure and avoid mechanical damage and metamorphism during transportation to Japan. We obtained two samples. One from surface 0.06 m in depth; the second from 0.10-0.16 m in depth. We cut the snow into rectangular blocks (0.05×0.05×0.06 m) using a hand saw, and put the block into a carton. We then immersed the carton with the 1-Bromododecane at −16 °C, which is lower than the melting point of the 1-Bromododecane (−10 °C). Before being immersed, the 1-Bromododecane was kept at a temperature of −6 °C using an insulating box in a tent, which is higher than the melting point. The concreted samples were transported in a frozen state, together with the ice core.

Furthermore on May 27, we sampled surface snow for carbonaceous aerosols. The samples were placed in a

![Fig. 4. Wire length by drilling time.](image-url)
pre-cleaned glass jar (8 L) using a clean stainless steel scoop. The samples were transported in a frozen state, together with the ice core.

5.3 Snow-pit observations

On May 26 and 27, we conducted snow-pit observations down to a depth of 3.5 m (Fig. 3C). The observation variables were snow temperature, stratigraphy, and density. Snow samples for chemical analysis were collected at 0.05 m depth intervals using stainless-steel tools, and each sample was placed in a separate polyethylene bag. Some samples for major ion and stable isotope analyses were melted in Whirl pack bags at Tasilaq. These snow temperature, stratigraphy, density, and chemical compositions are reported in Oyabu et al., (2016). The residue samples were transported in a frozen state, together with the ice core.

Additionally on May 27, we sampled snow at 0.50 m, 1.00 m, and 3.00 m in depth from the snow-pit wall for carbonaceous aerosols. The samples were placed in a pre-cleaned glass jar (8 L) using a clean stainless steel scoop. The samples were transported in a frozen state, together with the ice core.

5.4 Meteorological observations

We conducted meteorological observations during our stay at the field camp using a hand-held meteorological meter (Kestrel 4500NW) (Fig. 3D). Air temperature, air pressure, wind speed and direction, cloud type, cloud amount, and visibility were measured 42 times during the period from May 20 to June 2 (Table 3). When the sky was clear, we could see nunataks to the east. East from the SE-Dome site is one of the highest mountains in Greenland. Twice, blizzards were observed. When a blizzard occurred, north strong winds were present with less than 15 m s⁻¹ wind speed (Fig. 5). We did not perform any drilling work during the blizzard. All air temperatures recorded were within a range of −20°C to −10°C, with an average of −16.8°C. The average air pressure was 667 hPa. The relationship between air pressure (P; hPa) and height (h; m) is as follows:

\[
h = \frac{(P)}{(P_0)}-1 \times (7 + 273.15)
\]

where, \(P_0\) is 1013.25 hPa, and air temperature is −16.8°C. The calculated height (h) is 3265 m. On the other hand, GPS-based elevation was 3170 m above sea level. These results are higher than those (c.a. 3000 m) from satellite results (Helm et al., 2014).

<table>
<thead>
<tr>
<th>data</th>
<th>time</th>
<th>weather</th>
<th>wind dir.</th>
<th>wind speed(m/s)</th>
<th>Temp(°C)</th>
<th>air pressure (hPa)</th>
<th>visibility(km)</th>
<th>cloud amount</th>
<th>cloud shape</th>
<th>remarks</th>
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<tbody>
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<td>AM9:50</td>
<td>snow drifting</td>
<td>N</td>
<td>7.099</td>
<td>−20.9</td>
<td>665</td>
<td>0.1~0.2</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
<tr>
<td>21-May</td>
<td>AM7:00</td>
<td>snow drifting</td>
<td>N</td>
<td>7.011</td>
<td>−39.5</td>
<td>670</td>
<td>0</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
<tr>
<td>22-May</td>
<td>PM3:50</td>
<td>snow drifting</td>
<td>N</td>
<td>7.011</td>
<td>−39.5</td>
<td>670</td>
<td>0</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
<tr>
<td>23-May</td>
<td>AM6:00</td>
<td>snow drifting</td>
<td>NE</td>
<td>7.011</td>
<td>−39.5</td>
<td>670</td>
<td>0</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
<tr>
<td>24-May</td>
<td>PM3:50</td>
<td>snow drifting</td>
<td>NE</td>
<td>7.011</td>
<td>−39.5</td>
<td>670</td>
<td>0</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
<tr>
<td>25-May</td>
<td>AM6:00</td>
<td>snow drifting</td>
<td>NE</td>
<td>7.011</td>
<td>−39.5</td>
<td>670</td>
<td>0</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
<tr>
<td>26-May</td>
<td>PM3:50</td>
<td>snow drifting</td>
<td>NE</td>
<td>7.011</td>
<td>−39.5</td>
<td>670</td>
<td>0</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
<tr>
<td>27-May</td>
<td>AM6:00</td>
<td>snow drifting</td>
<td>NE</td>
<td>7.011</td>
<td>−39.5</td>
<td>670</td>
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<td>out of recognition</td>
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</tr>
<tr>
<td>28-May</td>
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<td>670</td>
<td>0</td>
<td>out of recognition</td>
<td>out of recognition</td>
<td>Bیدر</td>
</tr>
</tbody>
</table>

Table 3. SE-Dome meteorological data during our stay. Hypsens indicate no measurement of items.
6. Preliminary results of aerosol characteristics in SE-Dome surface snow

Preliminary analysis of aerosols shows BC, OC, dust, ion concentrations and chemical compositions of nonvolatile materials present in SE-Dome surface snow on May 27, 2015. The BC, OC, and dust concentrations were measured at the Meteorological Research Institute in Japan using the method described by Aoki et al. (2014). Ion concentrations were measured at the Institute of Low Temperature Science at Hokkaido University following the method described by Oyabu et al., (2016). These concentrations were averaged within 0.10 m in depth from the surface. Chemical compositions of nonvolatile materials in snow were measured at 0.05 m in depth at the Institute of Low Temperature Science at Hokkaido University, following the method described by Izuka et al. (2009; 2012). We sublimated the snow sample and analyzed nonvolatile particles using scanning electron microscopy/energy dispersive spectroscopy (SEM-EDS; JSM-6360 LV (JEOL) SEM & JED2201 (JEOL) EDS). Constituent elements of the particles were determined by SEM-EDS at 20 keV. The elements detected were O, Si, Al, S, Cl, Na, Mg, and Ca. The measured density within 0.10 m of the surface is 260 kg m$^{-3}$. (Oyabu et al., 2016) and the assumed accumulation rate is 0.9 m y$^{-1}$ in water equivalent (Pedro et al., 2012), therefore the surface 0.10 m correspond to 0.029 year (i.e. about 10 days of spring in 2015) in average resolution.

The BC concentration is nearly below the detection limit (Table 4). Even if we take into account underestimation due to low collection efficiency of the quartz fiber (10–38% in Torres et al., (2014), the result shows a concentration that is still too low compared to other regions in Greenland (about 2 ppbw from 1950 to 2000 in McConnell et al., 2007; 0.4 ppbw from June 28 to July 4 2012 in Aoki et al., 2014). One possible explanation is that huge snow accumulation dilutes mass flux of long-distance transported materials such as BC. On the other hand, OC and dust concentrations (Table 4) are the same or higher than the other regions in Greenland (e.g. 34 and 84 ppbw, respectively, in Aoki et al., 2014). This may be due to the fact that there are nunataks near the SE-Dome area, which are considered to be a source of dust, or the same as the maximum time for long-distance dust transport in the spring (Sun et al., 2001; Roe, 2009).

Major cations and anions were NH$_4$$^+$ and NO$_3$$^-$, respectively (Table 4 and Fig. 6A), which indicates a high contribution of continental biogenic emission from bacterial decomposition and biomass burning (e.g. Fuhrer et al., 1996) and/or anthropogenic materials, at least this spring. Most of ions have a low concentration compared to other regions in Greenland (Oyabu et al., 2016). These low concentrations may be due to the highland dome of the ice sheet or dilution of mass flux by high snow accumulation. Looking at the comparison in ppb units, ion concentrations are lower than dust concentrations. Even if the SE-Dome area is located in a coastal region of Greenland Ice Sheet, sea salt contribution (Cl$^-$) is lower than acidic materials (SO$_4$$^{2-}$ and NO$_3$$^-$) in the surface snow. Soluble continental material (Ca$^{2+}$) is almost the same as the sea salt concentration (Na$^+$). In summary, contribution of these aerosols to the SE-Dome area in this spring is too low compared with those in other regions in Greenland, but the contribution order is: 1) insoluble dust, 2) acidic materials (anthropogenic materials), 3) organic carbon and continental biogenic emission from microorganisms, 4) sea salt and soluble terrestrial material, and 5) black carbon below the detection limit.

Elemental distributions of Si, S, Cl, Na, and Ca are shown in Fig 7. The main component of nonvolatile particles was Si. Recent studies which used similar analyses indicated that Si, S, and Cl are originated from silicate minerals, sulfate salt, and chloride salts, respectively (Izuka et al., 2012). The result of the high Si-containing ratio to total particles (115/205) supports the idea that insoluble dust is the major aerosol, as shown in Table 4. In sulfate and chloride salts, particles containing S and Ca were the major constituents (Fig 6B, and 6C). The numbers of particles containing S and Ca particles were 51 out of 205, of which 21 were rectangular under SEM (Fig. 8), and are likely to consist of gypsum (Monoclinic crystal system). Gypsum is a primary aerosol of terrestrial origin, suggesting those aerosols are not formed in the atmosphere by H$_2$SO$_4$ in spite of the contribution of highly acidic aerosols. This result indicates that a certain amount of primary aerosol is preserved in the surface snow of SE-Dome. On the other hand, the numbers of particles containing S and Na were 5 per 205, and particle containing Cl and Na was none (0) per 205. Also, the numbers of particles containing Cl were only 2 per 205. These results suggest that there chloride salts are rarely present in the surface snow, implying most of sea salt has been altered due to secondary aerosols such as Na$_2$SO$_4$. Note that major soluble salts are not only CaSO$_4$ and Na$_2$SO$_4$ because there were many particles of Na without
Table 4. Aerosol concentrations in ppbw. Left: concentrations of organic carbon (OC), black carbon (BC), and dust. Right: ion concentrations. Lowest lines in the tables show weighted average from surface to 0.1 m depth.

<table>
<thead>
<tr>
<th>Depth</th>
<th>OC</th>
<th>BC</th>
<th>Dust</th>
<th>Depth</th>
<th>CH3SO4^+</th>
<th>Cl^-</th>
<th>SO4^2-</th>
<th>NO3^-</th>
<th>Na^+</th>
<th>NH4^+</th>
<th>Mg^2+</th>
<th>Ca^2+</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00–0.02 m</td>
<td>18.3</td>
<td>0.0</td>
<td>87.7</td>
<td>0.00–0.05 m</td>
<td>1.4</td>
<td>10.5</td>
<td>18.7</td>
<td>53.3</td>
<td>3.7</td>
<td>11.0</td>
<td>0.3</td>
<td>2.4</td>
</tr>
<tr>
<td>0.02–0.10 m</td>
<td>12.3</td>
<td>0.1</td>
<td>54.7</td>
<td>0.05–0.10 m</td>
<td>1.5</td>
<td>8.7</td>
<td>16.3</td>
<td>50.7</td>
<td>0.7</td>
<td>8.1</td>
<td>0.2</td>
<td>2.0</td>
</tr>
<tr>
<td>weighted average</td>
<td>13.5</td>
<td>0.1</td>
<td>61.3</td>
<td>weighted average</td>
<td>1.5</td>
<td>9.6</td>
<td>17.5</td>
<td>52.0</td>
<td>2.2</td>
<td>9.5</td>
<td>0.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Fig. 6. A) Fraction of ion species in equivalent. B) Fraction of elemental distribution of nonvolatile particles focusing on particles containing Ca and Na. C) Fraction of elemental distribution of nonvolatile particles focusing on particles containing S and Cl.

S nor Cl (13/205); Ca without S nor Cl (13/205); and S without Na, Mg nor Ca (34/205) (Fig. 6B, and 6C). These particles may contain NaNO3, CaCO3, and (NH4)2SO4, respectively. Ion concentration of high NH4^+ and NO3^- fraction (Table 4) and previous studies in Greenland (Iizuka et al., 2008) support the existence salts such as NaNO3 and (NH4)2SO4. Further analyses are needed in order to make clear the characteristics of aerosols in the SE-Dome area.

7. Conclusions

We drilled a 90.45 m ice core in a high accumulation area of the southeastern Greenland Ice Sheet. The SE-Dome site (67.18°N, 36.37°W, 3170 m a.s.l) is located 185 km north of the town of Tasilaq in southeastern Greenland. This is the first ice core drilling expedition from Japan, so we pioneered logistics for the base town Tasilaq, our camp, and ice core transportation back to Japan. We stayed on the SE-Dome area from May 18 to June 2, 2015, and drilled the ice core from May 22–27. There were two blizzards during our stay. The borehole temperature at 20 m depth was −20.9°C on May 26. We also performed aerosol, precipitation, surface snow, and snow-pit measurements to a depth of 3.5 m, and 42 meteorological observations at our field camp during our stay. The ice cores and snow samples were transported by a 20ft reefer, returning to the Institute of Low Temperature Science at Hokkaido University on August 24. We confirmed that all ice cores and snow samples are of high quality and did not maintain any damage during transportation, or after their arrival. Aerosol concentrations in the surface 0.1 m of snow from the SE-Dome site in this spring are too low compared to other region in Greenland, however, the contribution order is: 1) insoluble dust, 2) acidic materials (an-
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