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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℃ 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℃ 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 DML (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

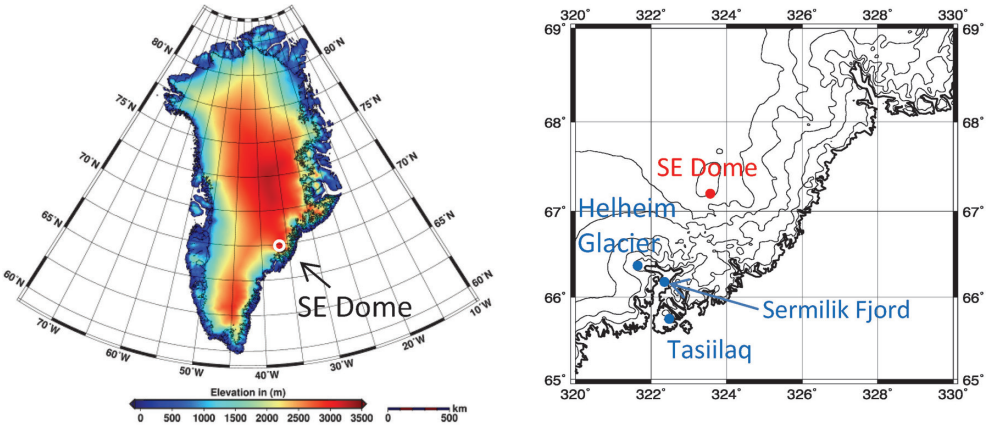


Fig. 1. Left: location of the SE-Dome. Base of Greenland elevation map is from Helm *et al.* (2014). Right: close up location of the SE-Dome.

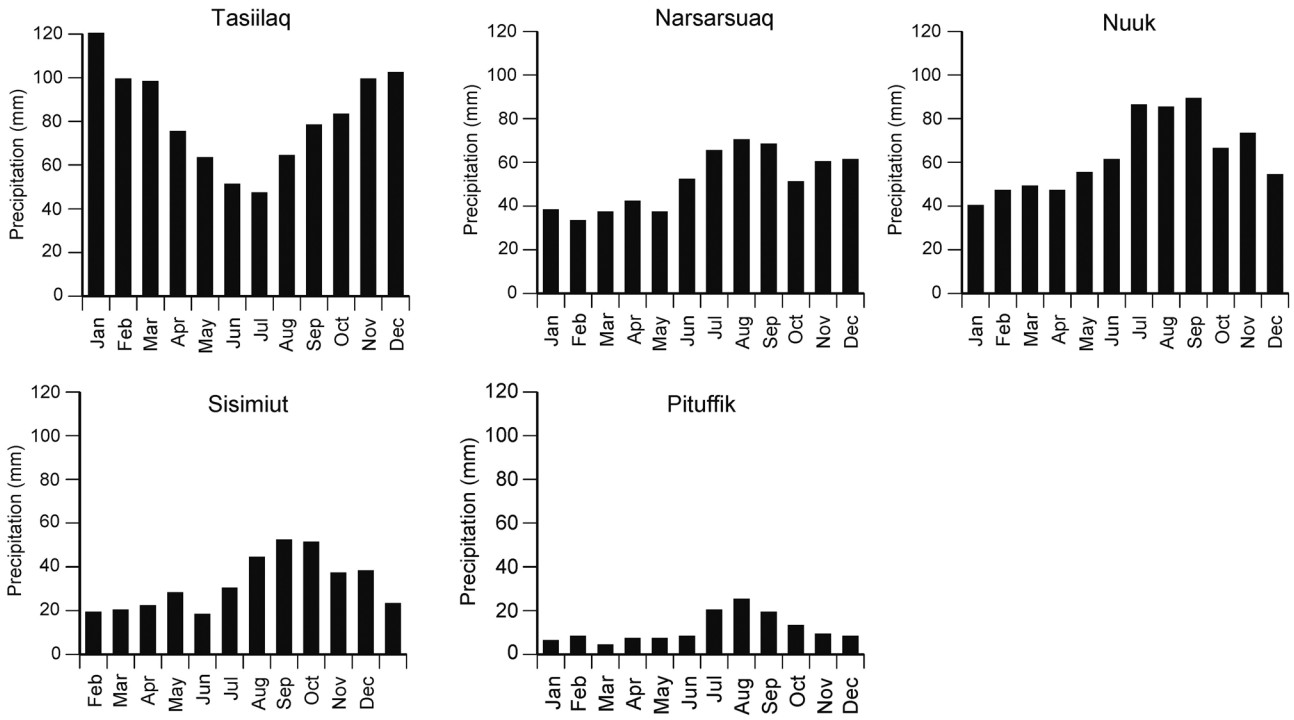


Fig. 2. Monthly precipitation average of several towns in Greenland from Cappelen *et al.* (2001).

(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 been not 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 Tasiilaq 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 Tasiilaq. 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 Tasiilaq was the base for this expedition; details are described in section 4.

Precipitation characteristics of Tasillaq 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 Tasiilaq. 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.

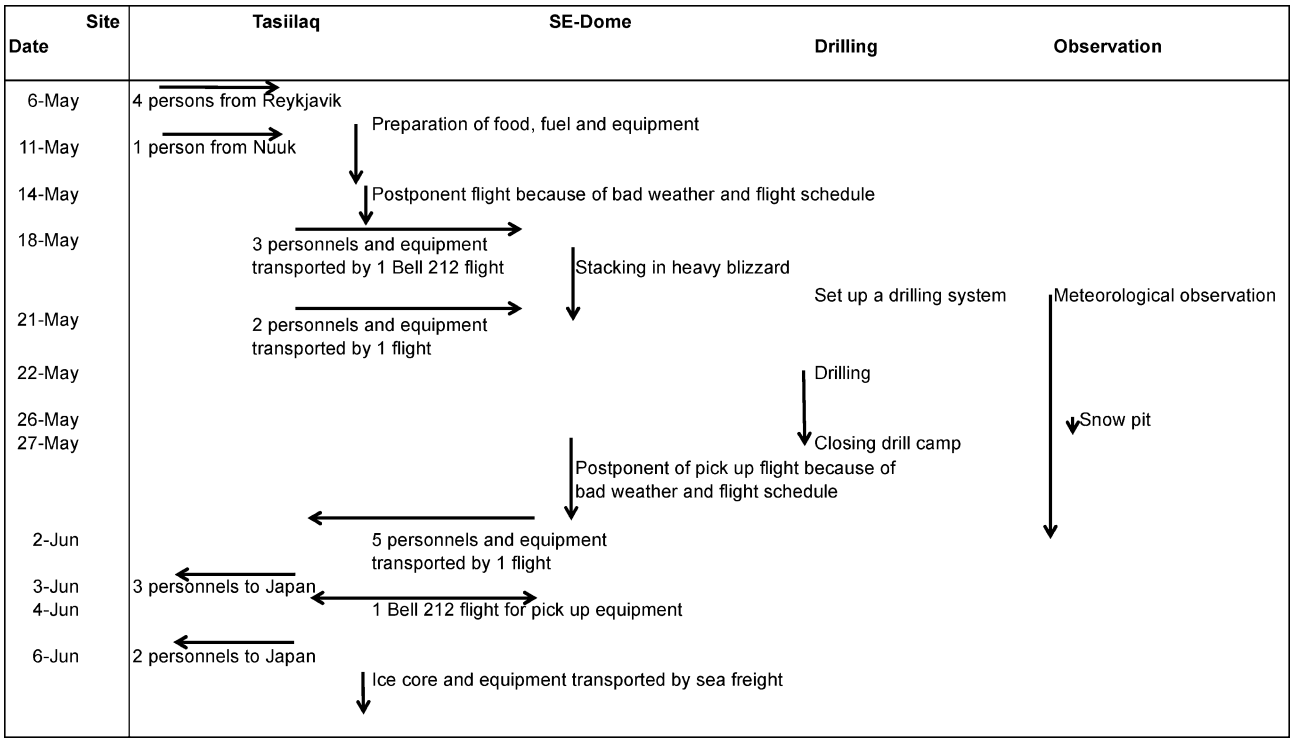
Some modelling and satellite analyses have studied characteristics of the SE-Dome area (Bales *et al.*, 2009; Burgess *et al.*, 2010; Hall *et al.*, 2013; Howat *et al.*, 2014; Helm *et al.*, 2014). These studies characterize the SE Dome areas as having: 1) one of the highlands in Greenland that is more than 3,000 m above sea level; 2) relatively cold air temperatures below −20℃ 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 alminous (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 1. Itinerary of this project.



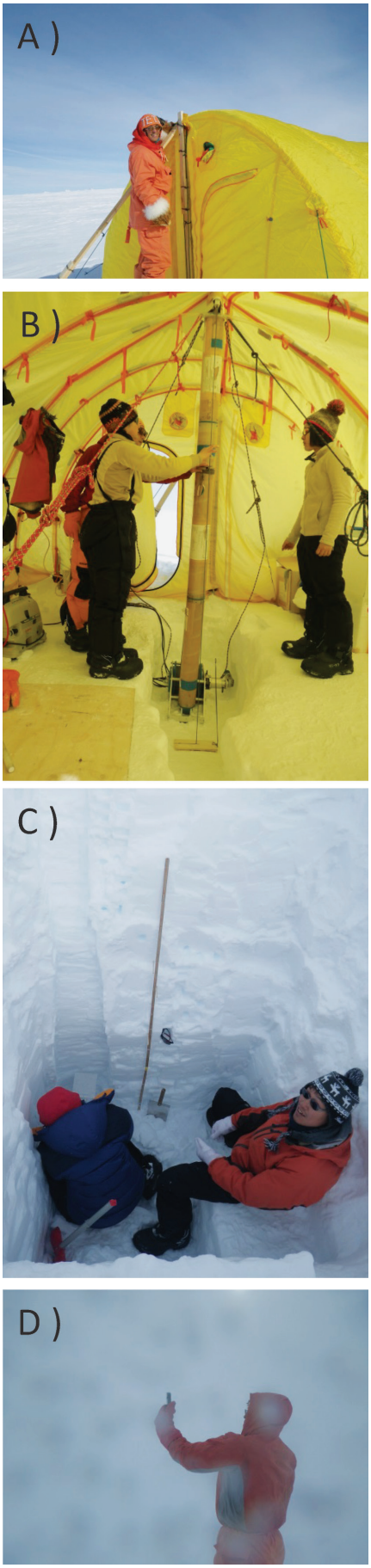


Fig. 3. Pictures of the SE-Dome observations. A) a drilling tent; B) drilling operation; C) pit observation; and D) meteorological observation.

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 Tasiilaq, Greenland, and flew personnel and equipment from Tasiilaq 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 Tasiilaq 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 Tasiilaq. 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℃ at the Pilersuisoq general store in Tasiilaq. The ice cores were then transported by a 20ft reefer on HEUNG-A AKITA 0013 vessel from Tasiilaq 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℃ 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.

Date	Run No.	Depth (m)	Pitch of Shoe (mm)	Remarks
22-May	1	0.00	7	No separator
	20	6.64		Separator
23-May	42	16.80		
24-May	83	42.00		
25-May	133	62.05		
	141	65.65	5	
	151	70.30	4	
26-May	161	75.02		
27-May	193	89.95		Kink of wire
	195	90.45		Kink of wire
				Breaking of electric wire

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 Tasiilaq 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℃. The room temperature near the drill winch in the drill tent just before the borehole measurement was −15.2℃. 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℃.

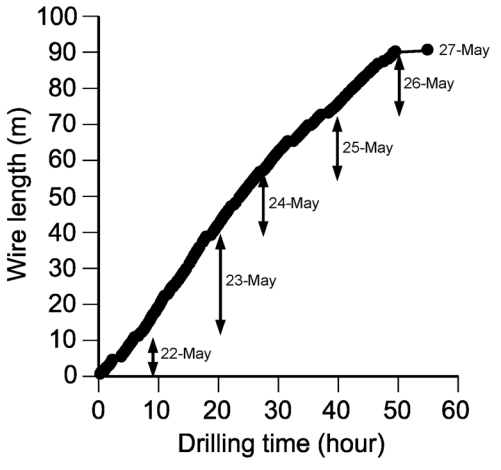


Fig. 4. Wire length by drilling time.

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, K040A025A). We collected aerosols in four periods; 1) 12:00 to 18:00 on May 26; 2) 8:00 to 16:50 on May 27; 3) 6:40 to 12:30 on May 28; and 4) 14:00 to 19:00 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 metamorphosis 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℃, which is lower than the melting point of the 1-Bromododecane (−10℃). Before being immersed, the 1-Bromododecane was kept at a temperature of −6℃ 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

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 Tasiilaq. 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℃ to −10℃, with an average of −16.8℃. The average air pressure was 667 hPa. The relationship between air pressure (P; hPa) and height (h; m) is as follows:

$$h=\frac{\left(\left(\frac{P}{P_0}\right)^{\frac{1}{5257}}-1\right)\times(T+273.15)}{0.0065} \quad \cdots (1)$$

where, P_0 is 1013.25 hPa, and air temperature is −16.8℃. The calculated height (h) is 3265 m. On the other hand, GPS-based elevation was 3,170 m above sea level. These results are higher than those (c.a. 3,000 m) from satellite results (Helm *et al*., 2014).

Table 3. SE-Dome meteorological data during our stay. Hyphens indicate no measurement of items.

data	time	weather	wind dir.	wind spped(m/s)	Temp.(℃)	air pressure (hPa)	visivility(km)	cloud amount	cloud shape	remarks
2015				() ; max. speed						
20-May	AM9:30	snow drifting	N	13.2(17.6)	—	—	0	out of recognition	out of recognition	Blizard
21-May	AM7:00	snow drifting (high)	N	9.1(11.7)	-20.3	659	0.2〜0.3	out of recognition	out of recognition	
21-May	PM3:50	clear	N	3.8(4.3)	-16.5	665	10〜15	5	3As, 2Cu	
22-May	PM1:30	snow storm	N	8.1(10.0)	-15.5	669	0.2〜0.3	8〜9	As,Ci	
22-May	PM6:00	snow storm	N	4.3(5.4)	-14.3	668	0.5	10	As	
23-May	AM6:00	snow	NW	3.0(3.8)	-17.2	663	5	10	As	
23-May	PM12:00	clear (slight snow)	SW	2.5(3.0)	-10.3	661	10	3	As	
23-May	PM6:00	clear	SW	2.8(3.3)	-11.9	660	>20	2	Cs	
24-May	AM6:00	snow	NW	0.3(0.5)	-10.4	662	15	10	As	
24-May	PM12:00	snow storm	W	5.3(7.2)	-13.9	665	0.5	10	As	
24-May	PM2:20	snow storm	E	8.1(9.9)	—	—	—	—	—	
24-May	PM6:00	snow storm	NE	8.6(10.0)	-15.3	666	0.1〜0.2	10	As	
24-May	PM6:50	snow storm	NE	9.5(11.6)	—	—	—	—	—	
25-May	AM6:00	snow drifting (high)	N	7.6(9.5)	-19.8	665	0.2〜0.3	out of recognition	out of recognition	
25-May	PM12:00	snow drifting (high)	N	7.1(8.6)	-17.5	667	0.2〜0.3	out of recognition	out of recognition	
25-May	PM6:00	cloudy	NW	6.7(7.9)	-17.1	667	5	9	Cs	
26-May	AM6:00	clear	NW	2.5(3.0)	-20.1	667	>20	1+	1cs, 0+Ci	
26-May	PM12:00	clear	NE	3.2(3.8)	-15.2	668	>20	2	Cs	
26-May	PM6:00	clear	NE	3.0(3.8)	-16.1	668	15	6	5Cs, 1As	
27-May	AM6:00	clear	SW	2.3(3.0)	-21.5	670	15	7	Cs	
27-May	PM12:00	clear	SE	3.0(3.9)	-15.2	671	10〜15	6	5Cs, 1As	
27-May	PM6:00	clear	SW	2.7(3.3)	-15.4	671	15〜20	2	1Cs, 1As	diamond dust
28-May	AM6:00	snow	NE	1.6(2.1)	-17.0	669	15	10	As	
28-May	PM12:00	snow	E	2.6(3.4)	-17.0	668	0.5	10	As	
28-May	PM6:00	snow	W	4.6(5.5)	-18.0	668	10	10	As	
29-May	AM6:00	snow storm	N	7.0(9.9)	-20.9	665	0.1〜0.2	out of recognition	out of recognition	
29-May	PM12:00	snow storm	N	11.3(14.0)	-19.5	667	0	out of recognition	out of recognition	Blizard
29-May	PM6:00	snow storm	N	15.0(18.1)	-18.2	663	0	out of recognition	out of recognition	Blizard
30-May	AM6:00	snow storm	N	13.8(16.1)	-20.2	663	0	out of recognition	out of recognition	Blizard
30-May	PM12:00	snow storm	N	14.9(19.2)	-19.5	663	0	out of recognition	out of recognition	Blizard
30-May	PM6:00	snow storm	N	13.2(15.3)	-19.2	667	0	out of recognition	out of recognition	Blizard
31-May	AM6:00	snow storm	NE	9.2(11.3)	-17.7	670	0.1	out of recognition	out of recognition	
31-May	AM8:50	snow drifting (high)	N	9.4(12.2)	—	—	0.2〜0.3	—	—	
31-May	AM11:20	cloudy	NE	6.0(7.5)	—	—	1〜2	—	—	
31-May	PM2:50	snow drifting (high)	NE	8.1(9.7)	—	—	0.2〜0.3	—	—	
31-May	PM6:00	clear	NW	5.7(7.1)	-16.0	672	10	3	Ci	
1-Jun	AM6:00	clear	NW	4.2(5.3)	-19.7	670	10	1〜2	Ci	
1-Jun	PM12:00	snow drifting (high)	NW	8.3(10.3)	-17.2	672	0.5	out of recognition	out of recognition	
1-Jun	PM12:55	snow drifting (high)	N	6.0(7.3)	—	—	5	—	—	
1-Jun	PM6:00	snow drifting (high)	NW	5.4(6.5)	-17.8	672	5〜10	8	5As, 3Ci	
2-Jun	AM6:00	cloudy	NW	1.7(2.2)	-20.1	672	15〜20	9+	As	
2-Jun	PM12:50	clear	NW	1.1(1.4)	-8.0	674	>20	5	4Ci, 1Cu	

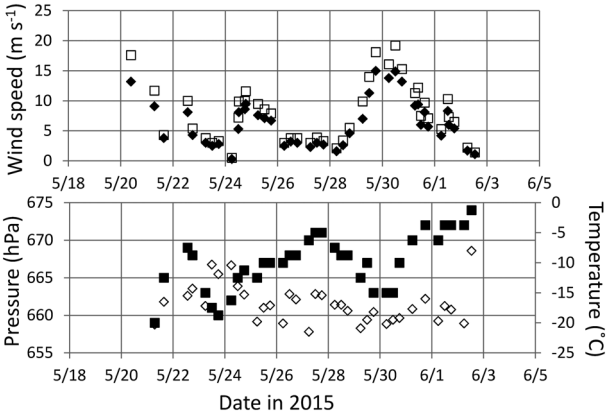


Fig. 5. Wind speeds (m s^{-1}) of max (□) and average (◆) values, air pressure (■; hPa), and air temperature (◇; ℃) during our stay.

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 Iizuka *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 efficiently 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.* 3.4 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 (Iizuka *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_2SO_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_2SO_4. Note that major soluble salts are not only $CaSO_4$ and Na_2SO_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.

Depth	OC	BC	Dust
0.00–0.02 m	18.3	0.0	87.7
0.02–0.10 m	12.3	0.1	54.7
weigted average	13.5	0.1	61.3

Depth	$CH3SO3^-$	Cl^-	SO_4^{2-}	NO_3^-	Na^+	$NH4^+$	Mg^{2+}	Ca^{2+}
0.00–0.05 m	1.4	10.5	18.7	53.3	3.7	11.0	0.3	2.4
0.05–0.10 m	1.5	8.7	16.3	50.7	0.7	8.1	0.2	2.0
weigted average	1.5	9.6	17.5	52.0	2.2	9.5	0.2	2.2

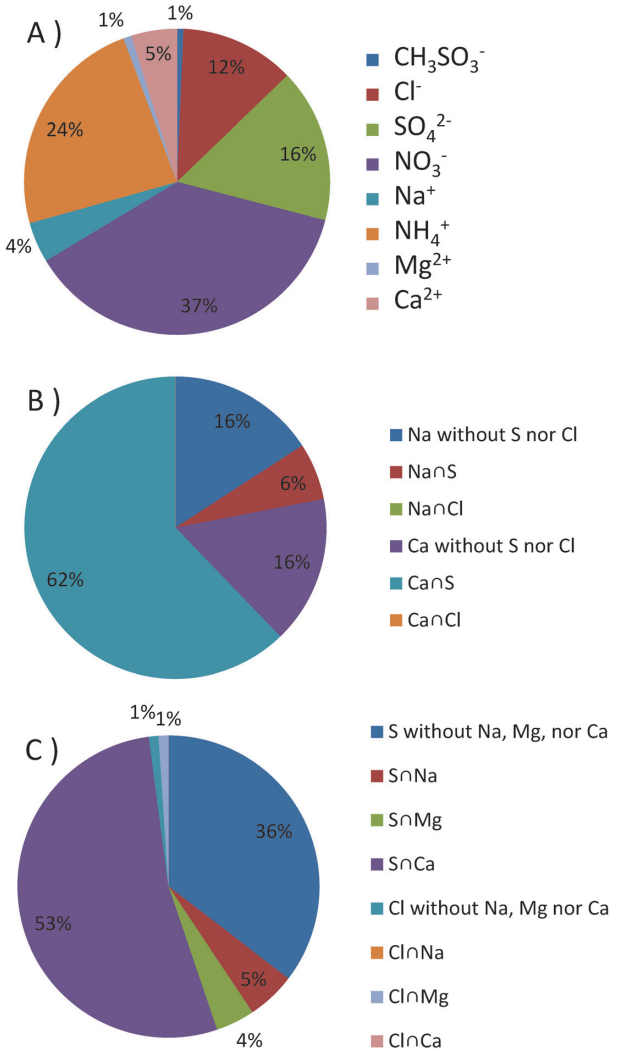


Fig. 6. A) Fraction of ion species in equivalent. B) Fraction of elemental distribution of nonvolatile particles focusing on particles containing Ca and Na. C) Fraction of elemental distribution of nonvolatile particles focusing on particles containing S and Cl.

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 $NaNO_3$, $CaCO_3$, and $(NH_4)_2SO_4$, respectively. Ion concentration of high NH_4^+ and NO_3^- fraction (Table 4) and previous studies in Greenland (Iizuka *et al.*, 2008) support the existence salts such as $NaNO_3$ and $(NH_4)_2SO_4$. Further analyses are needed in order to make clear the characteristics of aerosols in the SE-Dome area.

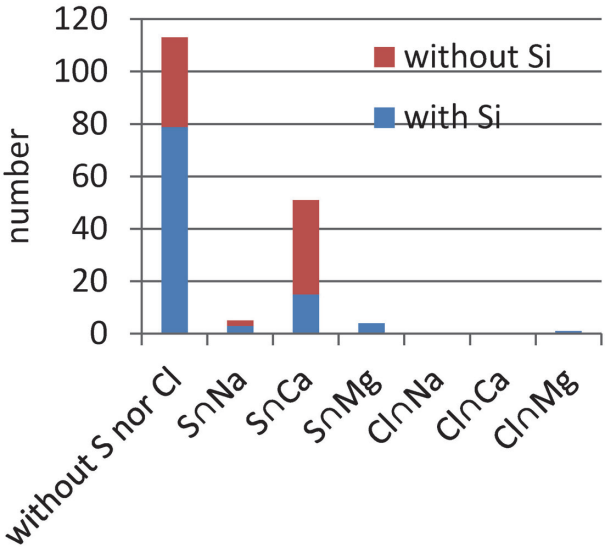


Fig. 7. Elemental distributions of nonvolatile particles. Blue and red bars show the number of particles detected with Si and without Si, respectively. From left bars, numbers of particles detected without S nor Cl, with S and Na, with S and Ca, with S and Mg, with Cl and Na, with Cl and Ca, with Cl and Mg.

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 Tasiilaq in southeastern Greenland. This is the first ice core drilling expedition from Japan, so we pioneered logistics for the base town Tasiilaq, 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℃ 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-

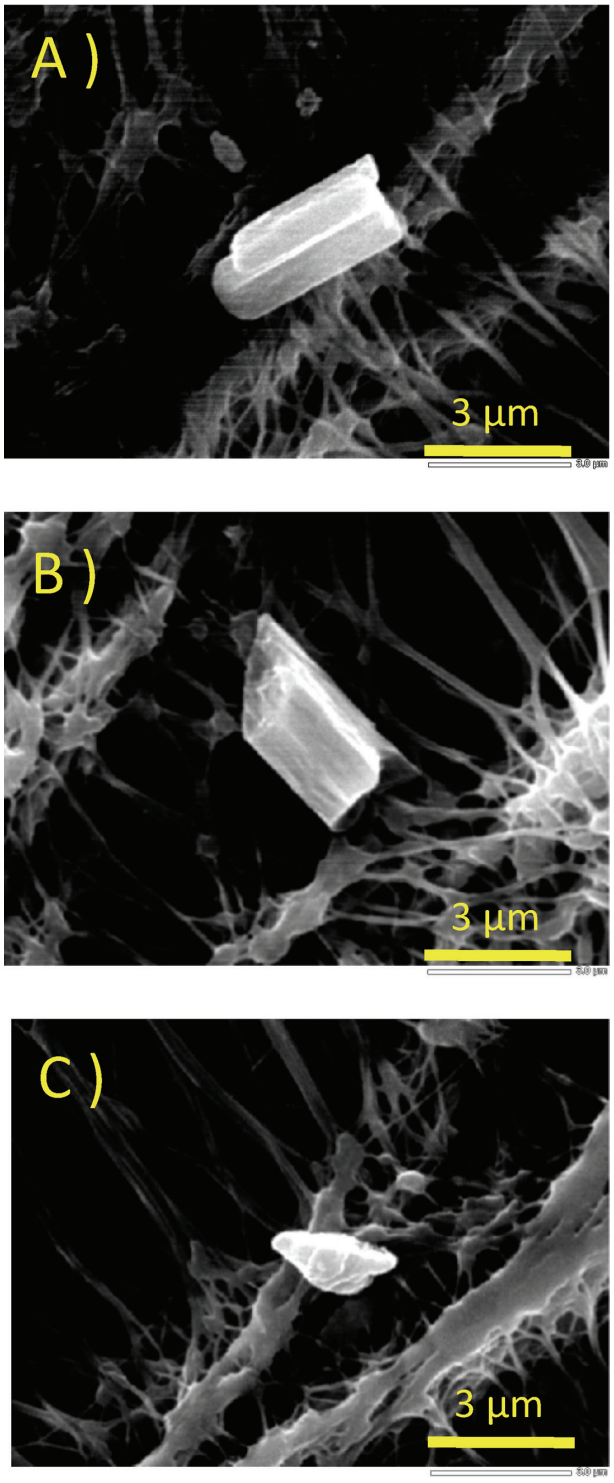


Fig. 8. Examples of micrograph of particles containing S and Ca. The particles can be divided into two groups; one is rectangular shape (A and B), the other is not crystalline form (C).

thropogenic materials), 3) organic carbon and continental biogenic emission from bacterial decomposition and biomass burning, 4) sea salt and soluble terrestrial material, and 5) black carbon below detection limit. We are now shifting from field logistics to continued science analyses in order to accomplish the remainder of this project, namely: 1) reconstruction of anthropogenic aerosols from Europe under the Icelandic low with high time resolution, and 2) further understand the snow densification mechanism at the high accumulation dome in Greenland.

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References

Andresen, C. S., Straneo, M. H. Ribergaard, M. H., Bjørk, A. A., Andersen, T.J., Kuijpers, A., Nørgaard-Pedersen, N., Kjær, K. H., Schjøth, F., Weckström, K. and Ahlstrøm, A. P. (2012): Rapid response of Helheim Glacier in Greenland to climate variability over the past century. *Nature Geoscience*, **5**, 37–41 doi:10.1038/ngeo1349.

Aoki, T., Matoba, S., Uetake, J., Takeuchi, N. and Motoyama, H. (2014): Field activities of the "Snow Impurity and Glacial Microbe effects on abrupt waring in the Arctic" (SIGMA) Project in Greenland in 2011–2013. *Bull. Glaciol. Res.*, **32**, 3–20, doi: 10.5331/bgr.32.3.

Bales, R. C., Guo, Q., Shen, D., McConnell, J. R., Du, G., Burkhart, J. F., Spikes, V. B., Hanna, E. and Cappelen, J. (2009): Annual accumulation for Greenland updated using ice core data developed during 2000–2006 and analysis of daily coastal meteorological data. *J. Geophys. Res.*, **114**, D06116, doi:10.1029/2008 JD011208.

Bamber, J. L., Griggs, J. A., Hurkmans, R. T. W. L., Dowdeswell, J. A., Gogineni, S. P., Howat, I., Mouginot, J., Paden, J., Palmer, S., Rignot, E. and Steinhage D. (2013): A new bed elevation data-set for Greenland. *The Cryosphere*, **7**, 499–510, doi:10.5194/tc-7-499-2013.

Banta, J. R., McConnell, J. R., Edwards, R. and Engelbrecht, J. P. (2008): Delineation of carbonate dust, aluminous dust, and sea salt deposition in a Greenland glaciochemical array using positive matrix factorization. *Geochem. Geophys. Geosyst.*, **9**, Q07013, doi:10.1029/2007GC001908.

Bory, A. J.-M., Abouchami, W., Galer, S. J. G., Svensson, A., Christensen, J. N. and Biscaye, P. E. (2014): A Chinese Imprint in Insoluble Pollutants Recently Deposited in Central Greenland As Indicated by Lead Isotopes. *Environ. Sci. Technol.*, **48**, 1451–1457, dx.doi.org/10.1021/es4035655.

Buchardt, S. L., Clausen, H. B., Vinther, B. M. and Dahl-Jensen, D. (2012): Investigating the past and recent δ^{18}O-accumulation relationship seen in Greenland ice cores. *Climate of the Past*, **8**, 2053–2059,doi: 10.5194/cp-8-2053-2012.

Burgess, E. W., Forster, R. R., Box, J. E., Mosley-Thompson, E.,

Bromwich, D. H., Bales, R. C. and Smith, L. C. (2010): A spatially calibrated model of annual accumulation rate on the Greenland Ice Sheet (1958–2007). *J. Geophys. Res.*, **115**, F02004, doi:10.1029/2009 JF001293.

Cappelen. J., Jørgense, B. V., Laursen, E. V., Stannius L. S. and Thomsen, R. S. (2001): The observed climate of Greenland, 1958–99 - with climatological Standard Normals, 1961–90. Danish Meteorological Institute Technical Report, 00–18.

EPICA community members. (2004): Eight glacial cycles from an Antarctic ice core. *Nature*, **429**, 623–628, doi:10.1038/nature 02599.

EPICA community members. (2006): One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, **444**, 195–198, doi:10.1038/nature05301.

Fischer, H., Wagenbach, D. and Kipfstuhl, J. (1998): Sulfate and nitrate firn concentrations on the Greenland Ice Sheet: 1. Large scale geographical deposition changes. *J. Geophys. Res.*, **103** (D17): 21927–21934, doi: 10.1029/98 JD01885.

Fuhrer, K., Neftel, A., Anklin, M., Staffelbach, T., and Legrand, M. (1996). High-resolution ammonium ice core record covering a complete glacial-interglacial cycle, *J. Geophys. Res.* **101**, D12, 4147–4164, DOI: 10.1029/95 JD02903.

Greenland Ice-core Project Members. (1993): Climate instability during the last interglacial period recorded in the GRIP ice core. *Nature*, **364**, 203–207.

Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S. and Jouzel, J. (1993): Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature*, **366**, 552–554, doi:10.1038/366552a0.

Hall, D. K., Comiso, J. C., DiGirolamo, N. E., Shuman, C. A., Box, J. E. and Koenig, L. S. (2013): Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS. *Geophys. Res. Lett.*, **40**, 1–7, doi:10.1002/grl.50240.

Helm, V., Humbert, A. and Miller, H. (2014): Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. *The Cryosphere*, **8**, 1539–1559, doi:10.5194/tc-8-1539-2014.

Howat, I. M., Negrete, A. and Smith, B. E. (2014): The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets. *The Cryosphere*, **8**, 1509–1518, doi:10.5194/tc-8-1509-2014.

Iizuka, Y., Horikawa, S., Sakurai T., Johnson, S., Dahl-Jensen, D., Steffensen, J. P. and Hondoh, T. (2008): A relationship between ion balance and the chemical compounds of salt inclusions found in the GRIP and Dome Fuji ice cores. *J. Geophys. Res.*, **113**, D07303, doi:10.1029/2007 JD009018.

Iizuka, Y., Miyake, T., Hirabayashi, M., Suzuki, T., Matoba, S., Motoyama, H., Fujii, Y. and Hondoh, T. (2009): Constituent elements of insoluble and nonvolatile particles during the Last Glacial Maximum of the Dome Fuji ice core. *J. Glaciol.*, **55** (191), 552–562, doi:10.3189/002214309788816696.

Iizuka, Y., Uemura, R., Motoyama, H., Suzuki, T., Miyake, T., Hirabayashi, M. and Hondoh, T. (2012): Sulphate-climate coupling over the past 300,000 years in inland Antarctica. *Nature*, **490**, 81–84, doi; 10.1038/nature11359.

IPCC. (2013): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.

Kameda, T., Motoyama, H., Fujita, S. and Takahashi, S. (2008): Temporal and spatial variability of surface mass balance at Dome Fuji, East Antarctica, by the stake method from 1995 to 2006. *J. Glaciol.*, **54**, 107–116, doi:10.3189/002214308784409062.

Matoba, S., Shimbori, K. and Shiraiwa, T. (2014): Alpine ice-core drilling in the North Pacific region. *Ann. Glaciol.*, **55** (68), 83–87, doi:10.3189/2014AoG68A020.

McConnell, J. R., Kipfstuhl S. and Fischer, H. (2006): The NGT and PARCA shallow ice core arrays in Greenland: A brief overview, *PAGES NEWS*, **14**, 1, hdl:10013/epic.24999.

McConnell, J. R., Edwards, R., Kok, G. L., Flanner, M. G., Zender, C. S., Saltzman, E. S., Banta, J. R., Pasteris, D. R., Carter, M. M. and JKahl, J. D. W. (2007): 20th century industrial black carbon emissions altered arctic climate forcing. *Science*, **317** (5843), 1381–1384, doi:10.1126/science. 1144856.

McConnell, J. R. and Edwards, R. (2008): Coal burning leaves toxic heavy metal legacy in the Arctic. *PNAS*, **105**, 34, 12141, doi: 10.1073/pnas.0803564105.

North Greenland Ice Core Project Members. (2004): High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature*, **431**, 147–151, doi:10.1038/nature02805.

Oyabu, I., Matoba, S., Yamasaki, T., Kadota, M. Y. and Iizuka, Y.(2016): Seasonal variations in the major chemical species of snow at the South East Dome in Greenland, Polar Science. doi:10.1016/j.polar.2016.01.003.

Pedro, J.B., McConnell, J. R., van Ommen, T. D., Fink, D., Curran, M. A. J., Smith, A. M., Simon, K. J., Moy, A. D. and Das, S. B. (2012): Solar and climate influences on ice core 10Be records from Antarctica and Greenland during the neutron monitor era. *Earth Planet. Sci. Lett.*, **355–356**, 174–186, doi:10.1016/j.epsl.2012.08.038.

Roe, G. (2009): On the interpretation of Chinese loess as a paleoclimate indicator. *Quat. Res.*, **71** (2), 150–161, doi:10.1016/j.yqres.2008.09.004.

Shiraiwa, T., Goto-Azuma, K., Matoba, S., Yamasaki, T., Segawa, T., Kanamori, S., Matsuoka, K. and Fujii, Y. (2003): Ice core drilling at King Col, Mount Logan 2002. *Bull. Glaciol. Res.*, **20**, 57–63.

Sun, J. M., Zhang, M. Y. and Liu, T. S. (2001): Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960–1999: Relations to source area and climate, *J. Geophys. Res.*, **106** (D10), 10,325–10,333, doi:10.1029/2000 JD900665.

Torres, A., Bond, T. C., Lehmann, C. M. B., Subramanian, R. and Hadley, O. L. (2014): Measuring organic carbon and black carbon in rainwater: Evaluation of methods. *Aerosol Sci. Technol.*, **48**, 238–249, doi:10.1080/02786826.2013.868596.

Watanabe, O., Jouzel, J., Johnsen, S., Parrenin, F., Shoji, H. and Yoshida, N. (2003): Homogeneous climate variability across East Antarctica over the past three glacial cycles. *Nature*, **422** (6931), 509–512, doi:10.1038/nature01525.