Elemental carbon distribution in Svalbard snow

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Abstract.

The concentration of apparent elemental carbon (EC$_a$, based on a thermal-optical method) in the snow was investigated in Svalbard (European Arctic), during spring 2007. The median EC$_a$-concentration of 81 samples was 4.1 µg l$^{-1}$ and the values ranged from 0 to 80.8 µg l$^{-1}$ of melt water. The median concentration is nearly an order of magnitude lower than the previously published data of equivalent black carbon (BC$_e$, based on an optical method), obtained from Svalbard snow in the 1980s. A systematic regional difference was evident: EC$_a$ concentrations were higher in East-Svalbard compared to West-Svalbard. The observations of snow EC$_a$ cover spatial scales up to several hundred kilometers, which is comparable to the resolution of many climate models. Measurements of atmospheric carbonaceous aerosol (2002–2008) at Zeppelin station in Ny-Ålesund, Svalbard, were divided to air mass sectors based on calculated back-trajectories. The results show that air originating from the eastern sector contains more than two and half times higher levels of soot than air arriving from South-West. The observed East-West gradient of EC$_a$-concentrations in snow may be due to a combination of the atmospheric concentration gradient, the orographic effect of the archipelago, and the efficient scavenging of the carbonaceous particles through precipitation.
1. Introduction

Carbonaceous aerosol particles are emitted from both natural (forest fires) and anthropogenic (biomass and fossil fuel burning) combustion sources. These particles, often called soot, cause a net positive climate forcing (Forster et al. [2007], Hansen and Nazarenko [2004], Jacobson [2002]). The forcing is due to light absorption by the particles, which lowers the surface albedo on snow and ice covered areas (Hansen and Nazarenko [2004]) and heats the atmosphere via three mechanisms: the direct effect (e.g., Schulz et al. [2006], Chýlek and Wong [1995]), the indirect effect (e.g., Hansen et al. [1997]), and the semi-direct-effect (e.g., Johnson [2003]).

Model calculations suggest a 10% reduction of the spectraly averaged albedo for soot content of about 1000 µg l\(^{-1}\) for fresh snow (grain radius 0.1 mm). For old melting snow (grain radius 1 mm) a soot concentration one fifth of that is needed for 10% albedo reduction. (Warren and Wiscombe [1985]) The small initial darkening of the snow speeds up the grain growth and the melt, which leads to further albedo reduction. The largest forcing coincides with the onset of spring melt (Flanner et al. [2007]). Together with several other features, such as the increase of the absorption by soot as a function of snow grain size (Warren and Wiscombe [1980]), this leads to positive feedbacks. The result is a climatic forcing with high efficacy (Flanner et al. [2007], Hansen and Nazarenko [2004]). However, there are large gaps in understanding the transport and deposition of carbonaceous aerosol particles to the Arctic snow pack. Also, the above mentioned modeling results remain to be verified by in-situ measurements.
Carbon dioxide, with long atmospheric lifetime, is the cause for most of the human-induced warming (Forster et al. [2007]). However, short-lived pollutants, like soot, have drawn both scientific and political interest because a reduction of these emissions would result in much faster lowering of their climate forcing (Quinn et al. [2007]).

The previous soot measurements in the Arctic snow pack are few and mainly from the 1980s (Table 1, See Flanner et al. [2007] for more complete listing). The objective of this work is to study the present-day carbonaceous aerosol particle distribution in snow in Svalbard, and compare these findings to concentrations measured in the air.

The atmospheric transport of soot to Svalbard was studied by connecting atmospheric soot measurements to back-trajectory calculations, in order to understand the observed regional (∼100 km) scale variability in the snow pack.

2. Data collection and methods

2.1. Field area and snow sampling

Svalbard is situated between 74 and 81 degrees North in the European sector of the Arctic (Figure 1). The archipelago, 60% of which are covered by ice (Hagen et al. [2003]), is well suited for studies of long-distance transport and deposition processes as local sources are few and essentially limited to the settlements Longyearbyen (c. 2000), Barentsburg (c. 500), Svea (c. 250), Polska Stacja Polarna in Hornsund (c. 8–25) and Ny-Ålesund (c. 40–150 inhabitants) (Figure 1). A trajectory climatology study (Eneroth et al. [2003]), atmospheric measurements (Stohl et al. [2007], Staebler et al. [1999]), and snow- and ice core studies (Hicks and Isaksson [2006], Hermanson et al. [2005]) confirm that long-distance transport of pollutants from lower latitudes reaches Svalbard.
The cyclonic activity over the Norwegian Sea, combined with orographic lifting of the air masses, brings more precipitation to Svalbard than to the generally dry surrounding Arctic. During precipitation the main wind direction is from east or south-east, which are expected to be the main directions for the air pollution transport (Semb et al. [1984]).

The eastern parts of the archipelago are known to have the highest precipitation due to the easterly winds produced by the low pressure systems traveling over the Barents Sea region, south of Svalbard (Hisdal [1976]). The melt season on the Svalbard ice caps starts between late May and late June and ends between late August and the beginning of October (Sharp and Wang [2009]). The areas north and east from Svalbard is covered with sea ice a major part of the year.

Eighty-one samples from the winter snow pack were collected during several field campaigns in February–April 2007. At each of the seven field sites (Figure 1, Table 2) 5–12 samples were collected, apart from the Brøggerhalvøya (Ny-Ålesund) area where a more extensive sampling was conducted (39 samples). The campaign concentrated on surface samples (typically down to 5 cm depth), but at most of the sites the whole seasonal snow column below was sampled. At Holtedahlfonna, Kongsvegen, Linnébreen, Lomonosovfonna and Austfonna the samples were taken on glaciers, while on Brøggerhalvøya and in Inglefieldbukta samples collected on tundra and landfast sea ice were included.

2.2. Instrumentation and sample analysis

The snow was collected in glass jars, melted at room temperature, and filtered through quartz microfiber substrates. The Thermal/Optical Carbon Aerosol Analyzer (Sunset Laboratory Inc., Forest Grove, USA), and the NIOSH 5040 protocol (Birch [2003]), were employed to obtain apparent elemental carbon (ECₐ) concentrations in the snow. (Here-
inafter the bracket notation for the mass concentrations is used, e.g., $[\text{EC}_a]$.) The carbon collected on the filter is divided into apparent organic (OC) (including carbonate (CC)) and elemental (EC$_a$) carbon depending on its volatilization temperature. First, a punch of typically $1 \, \text{cm}^2$ cut from the filter is heated to $860 \, ^\circ\text{C}$ in a He-atmosphere for releasing OC and CC. In the second stage of the analysis EC$_a$ is released by heating of the filter substrate in an oxygen-helium atmosphere. The released CO$_2$ is reduced to CH$_4$ for detection by a flame ionization detector (FID). The transmittance of the filter is monitored optically using laser light, which allows the correction for pyrolysis (charring) occurring during the analysis. The apparent elemental carbon, EC$_a$, is used as a proxy for the light absorbing carbonaceous aerosol.

The atmospheric soot sampling and measurements are conducted at the station Zeppelin ($78^\circ54' \, \text{N} 11^\circ53' \, \text{E}, 474 \, \text{m.a.s.l.}$) near Ny-Ålesund, Svalbard (Fig. 1), using a filter based optical method. A custom built particle soot absorption photometer (PSAP) based on the integrating plate technique, is employed. The outcome of the measurement, equivalent black carbon (BC$_e$), is another widely used proxy for the light absorbing part of the carbonaceous aerosol. PSAP employs a LED (light-emitting diode) with a wavelength of $530 \, \text{nm}$ to illuminate two $3 \, \text{mm}$ diameter spots on a substrate (Tissuglass). The particles are collected from the air by flushing it through the filter, keeping one of the spots clean for reference. The evolution of the filter transmittance is measured in order to derive the light extinction coefficient of the loaded filter.

As light extinction is the sum of absorption and scattering, a correction for the scattering is needed to obtain an estimate of the absorption coefficient ($b_{\text{abs}}$) of the loaded filter. Also, the effect that the filter loading has on the extinction needs to be taken
in consideration. Both corrections were done following Bond et al. [1999]. Data from a TSI 3563 Nephelometer was used for the correction for the light scattering particles. No adjustment was done for the small difference in wavelength between the Nephelometer (550 nm) and PSAP (530 nm) instruments. For details of the correction scheme used for PSAP, see Krecl [2008]. To convert $b_{abs}$ to mass concentration a specific absorption cross section ($\sigma_{abs}$) of 10 m$^2$g$^{-1}$ was used.

2.3. Trajectory analysis

Atmospheric back-trajectories were used to estimate the origin of the air. Trajectories give a better picture of the atmospheric transport paths than locally measured wind direction especially at locations like Svalbard, where the topography strongly influences the wind pattern. The NOAA HYbrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler and Rolph [2003]) was used for back-trajectory runs for the measurement period 2002–2008 calculating seven-day back-trajectories, ending at Zeppelin station location and altitude. The direction of the flow was defined as the angle of the sum vector based on the whole trajectory. Each of the vectors was linked to a six-hour average of hourly $[BC_e]$ measurements at Zeppelin and classified into one of the eight sectors (Fig. 2). The analysis comprising of 8359 trajectories, four for each day, are likely to capture the characteristic features of the relation between observed atmospheric $[BC_e]$ and airmass origin.
3. Results and discussion

3.1. ECₐ concentrations in the snow

The [ECₐ] in the snow from 86 samples (Table 2 and Figure 3) are low, as expected for remote Arctic sites. An exception is Linnébreen, which suffers from local pollution from the coal mining settlement Barentsburg, 15 km North-East of the sampling site (Fig. 1). The mean and median [ECₐ] (excluding the 5 samples from Linnébreen) calculated by giving an equal weight to each sample are 8.7 µg l⁻¹ and 4.1 µg l⁻¹, with the values ranging from 0 to 80.8 µg l⁻¹ of meltwater. The dataset is not a complete mapping of soot concentrations in Svalbard, since the samples were collected during different field campaigns in spring 2007. Instead, it can be viewed as an insight into the range of variability. The linkages between [ECₐ] and the sampling site altitude and depth of the sample in the snow pack, were studied, but no evident correlation could be found.

A spatial difference in snow soot concentrations on the regional scale of 10–100 km (scales similar to scales resolved in climate models) was found. The medians of the ECₐ samples from the eastern and western parts of the archipelago were compared by applying the Kruskal-Wallis-test (Kruskal and Wallis [1952]). Brøggerhalvøya, Holtedahlfonna, and Kongsvegen were defined as western sites, and Austfonna, Lomonosovfonna, and Inglefieldbukta as eastern sites (Fig. 1). Linnébreen was left out of the comparison. The resulting p-value around 10⁻⁴ indicates that the median of the mass concentrations measured at the eastern sites (7.3 µg l⁻¹) was statistically larger than what was found at the western sites (2.7 µg l⁻¹) at a high confidence level. Especially the concentrations measured at Inglefieldbukta enhance the median of the eastern sites. To some extent this
pattern of larger $[\text{EC}_a]$ in East-Svalbard can be seen in the modeling results of Flanner et al. [2007] (their Fig. 5).

A concentration of $15 \mu g l^{-1}$ of soot in new snow reduces the spectral albedo at 470 nm (the most sensitive wavelength) by about 1% (Warren and Wiscombe [1985]), and can be considered a detection-threshold for spectrometers measuring albedo (Grenfell et al. [2002]). However, soot is much more effective in reducing the snow albedo for larger snow grains, as well as if the mixing between snow and soot grains is internal (Chýlek et al. [1983]). For melting old snow with large grains, only $3 \mu g l^{-1}$ would be needed to cause a 1% albedo reduction. In this study, 11% of the measurements exceeded the detection-threshold for new snow, and 63% for old snow. High concentrations were more common at the eastern sites.

### 3.1.1. Variability and uncertainties

The variability caused by the sampling and analytical method was studied by taking multiple samples from the same locations (within approximately one meter) and the same depths (approximately the top 5 cm) for six of the sites. The combination of the natural variability in the snow pack and the inherent uncertainties in the method caused large variations: the relative root mean square deviation within the multiple sample sets was, on average, 1.0.

One cause for the horizontal variability of snow impurity content at small scales is wind induced snow drift, an event common in Svalbard (Jaedicke [2001]). The enhanced sublimation on crystal surfaces during snow drift causes an increase in impurity concentrations (Pomeroy et al. [1991]), and together with the redistribution of snow, influences the impurity concentration distribution in snow.
A systematic sampling campaign covering the same time period would be needed to verify the East-West gradient of $[\text{EC}_a]$ in the Svalbard snow. Although the $[\text{EC}_a]$ median from eastern Svalbard is higher than the median from western Svalbard, this result is challenged by the limited number of samples, the heterogeneity in the sampling timing and strategy, and the observed variability within the multiple samples. Using $\text{EC}_a$ as a proxy for long distance transported soot might lead to an exaggerated estimate due to the possible presence of elemental carbon-containing soil dust in the snow samples.

A possible $\text{EC}_a$-negative artifact exists in the specific procedure used: the hydrophobic soot particles might attach to the walls of the sample jar as soon as the snow sample is in liquid form (Clarke and Noone [1985], Ogren et al. [1983]). The result from a laboratory experiment (Figure 4) showed that a significant reduction in the $[\text{EC}_a]$ required storing time longer than 1.5 days, indicating that the procedure of melting the samples in glass jars over night did not cause large losses.

Several techniques to measure light absorbing carbonaceous aerosols exist. As all of the techniques have their limitations, the observed concentrations are specific for the method used. Some of the previous measurements of soot in snow are listed in Table 1. Clarke and Noone [1985] measured $[\text{BC}_e]$ in spring of 1983, which are eight times higher than the median $[\text{EC}_a]$ (three and half times higher than the mean $[\text{EC}_a]$) of samples in this study. The $[\text{BC}_e]$ measured by Grenfell et al. [2002] on the sea ice in the central Arctic in 1998 had a mean of the same magnitude as the data presented here, but with less variability.

Clarke and Noone [1985] and Grenfell et al. [2002] used an optical analysis method, while a thermal-optical technique is used here. The methods give results which can differ up to factor of 7, while factor of 2 differences are common (Watson et al. [2005]). The thermal-
optical analysis is expected to underestimate the light absorbing material, since a part of the organic carbon (separated from the EC\textsubscript{a} in the thermal-optical analysis) is known to absorb light (Andreae and Gelencr [2006]). The outcome of the optical analysis, BC\textsubscript{e}, is, instead, the amount of the total light absorbing material on a sample filter, including minerals and organic matter. According to Watson et al. [2005], however, the differences between the methods are unsystematic. Advanced optical methods can separate dust from BC\textsubscript{e} using the spectral signature of the sample filter. Due to the discrepancies in the methods, it is not straightforward to conclude that the lower values presented here were solely due to the reductions in the aerosol levels after the 1980’s (Husain et al. [2008], Quinn et al. [2007]), although it may be part of the explanation.

3.2. Transport of atmospheric soot to Svalbard

The atmospheric time series of [BC\textsubscript{e}] for 2002–2008 shows that the measured concentrations in the air at Zeppelin are low apart from the springtime arctic haze (e.g., Stohl [2006], Shaw [1995]) events (Fig. 5). The mean [BC\textsubscript{e}] over the 6.5 years of measurements is 44 ngm\textsuperscript{-3}, while Eleftheriadis et al. [2009] reported 39 ngm\textsuperscript{-3} for 1998–2007 at the same site using Aethalometer. The mean [BC\textsubscript{e}] of the dataset of this study for January through March 2002–2008 is 73 ngm\textsuperscript{-3}. This value compares well with a model experiments (Koch and Hansen [2005]) suggesting black carbon concentrations of 50–100 ngm\textsuperscript{-3} for these months in the surface air in the Arctic. The Zeppelin station BC\textsubscript{e}-record is too short for any meaningful trend analysis. It is anyway evident from the data that 2007 and 2008 were lower in [BC\textsubscript{e}] than the earlier years.

The measured air [BC\textsubscript{e}] depends on the transport and precipitation history of the air mass. The trajectory sum vector calculations together with the air [BC\textsubscript{e}] data from
Zeppelin station show that air from the east contains over two and half times more BC$_e$ than air from south-west (Fig. 6 A and Table 3). This result is in agreement with Staebler et al. [1999], a study relating the Ny-Ålesund aerosol physical and chemical properties to their source region. Northern, northwestern and southern transport paths bring air with similar intermediate [BC$_e$] levels. In Figure 5 one can see the same pattern with polluted air arriving from northeast, east and southeast.

According to the back-trajectory runs, the air at Zeppelin mountain, Ny-Ålesund, arrives most often from the north (23%) or northeast (21% of the trajectories). Runs when the direction of the flow is from east (12%) and west (10% of the trajectories) are about half as frequent. Southern flow occured for only 5% of the trajectory runs. Most of the total carbonaceous aerosol burden arrives to Svalbard from the north and northeast (Fig. 6 B). This is due to the the northern and northeastern flows being the most frequent and having substantial [BC$_e$].

The high concentrations measured in the air arriving from the East and South-East is due to the source regions, Europe and North-Asia, which produce substantial soot emissions (Bond et al. [2004]). The cause for the low air [BC$_e$] in the southwesterly flow is most likely that the pollutants from North America or the North Atlantic ship traffic are removed by precipitation in the North Atlantic storm track (Shaw [1995]) or blocked by the high plateau of Greenland (Rahn [1981]). The [BC$_e$]-gradient in the incoming air does not alone cause the difference in snow [EC$_a$] at the eastern and western sites. A systematic scavenging of the western air at the west and the eastern air at the east coast, due to prevailing flow directions in combination to the orographic effect of the archipelago is a possible explanation for the observed pattern.
The $[\text{BC}_e]$ values were derived based on the specific absorption cross section ($\sigma_{\text{abs}}$) of 10 m$^2$g$^{-1}$. In the literature, values for $\sigma_{\text{abs}}$ of soot vary between 1 and 30 m$^2$g$^{-1}$ depending on the chemical composition, size and shape, and mixing state of the particles (Andreae and Gelencér [2006]). Bond and Bergström [2006] reports 7.5 m$^2$g$^{-1}$ for pure soot particles. For a remote site the particles are aged and $\sigma_{\text{abs}}$ is thus expected to be somewhat higher. The results from simultaneous EC$_a$ and BC$_e$ measurements are in good agreement (Forsström [2008]), which confirms that for atmospheric measurements the two methods can be used interchangeable (Krecl et al. [2007]) and that the value used for $\sigma_{\text{abs}}$ is reasonable for this specific site. Furthermore, the possible error from the choice of $\sigma_{\text{abs}}$ doesn’t influence the relative pattern of soot content of the air masses arriving from different directions (Fig. 6).

4. Conclusions

1. Apparent elemental carbon (EC$_a$) concentrations from 81 snow samples taken around Svalbard in spring 2007 are low, and show large variation at each of the 6 locations. The samples at the eastern side present statistically significantly higher values than those at the western side.

2. Linking the observed atmospheric equivalent black carbon BC$_e$ concentration at the Zeppelin station, Ny-Ålesund with air mass trajectories, shows that generally higher concentrations are observed when the air comes from the east than from west. This could be one factor to explain why the measured EC$_a$ content in snow in East-Svalbard presented systematically higher values compared to the western side.
3. The snow EC$_a$ data in this study are, in general, lower (on average by a factor of 4) than previous measurements of BC$_e$ from Svalbard reported by Clarke and Noone [1985]. For median values the difference is a factor of 8. Three factors contribute to the difference: (i) the lower atmospheric soot burden today compared to the 80’s, (ii) the two different methods for determining BC$_e$ and EC$_a$, and (iii) loss of carbon from the samples after collection.

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References


Forsstrm, S. (2008), Carbonaceous aerosol particles in Svalbard snow, Master’s thesis, Department of Physics, University of Helsinki; Norwegian Polar Institute.


Figure 1. The medians of apparent elemental carbon ($EC_a$) in $\mu g l^{-1}$ at seven sampling locations.

Figure 2. The division of the geographical area surrounding Svalbard to the eight sectors. The projections of the azimuth angels from Zeppelin are plotted on a stereographical map projection. Shoreline data from Matlab m map-package.

Figure 3. The measured apparent elemental carbon ($EC_a$) concentrations at each site except Linnbreen. The standard deviation from the mean (solid horizontal line) at each site is noted with an errorbar. The square marker is the median of the subset. The sites are plotted from west (on the left) to east.

Figure 4. A test was done for investigating the possible $EC_a$ losses as function of sample storing time in liquid form. Snow was melted in a large plastic container, mixed well and distributed to glass jars. The $[EC_a]$ was measured after 12, 36, 180 and 732 hours after the commencing of the melt. Three parallel samples measured at each time step are marked with white markers. The black squares indicate the means of the sample set and the error bars show the standard deviations from them.

Figure 5. Time series of atmospheric equivalent black carbon ($BC_e$) at Zeppelin station, Ny-Ålesund in 2002–2008. Concentrations in ng m$^{-3}$. The light gray markers indicate flow from northeast, east or southeast and dark gray markers flow from south, southwest or west.
Figure 6. A. Sector plot showing the connection between the measured air \([BC_e]\) and the direction of the flow according to the back-trajectory runs. The sectors are centered on Zeppelin station coordinates and altitude (474 m). The number of trajectories falling into each \(45^\circ\) sector is indicated by the number. The thick arc shows the median of the six-hours mean air \([BC_e]\) on when the mean vector of the corresponding back-trajectory falls into the sector. The innermost arc indicates the \(25^{th}\) percentile and the outermost arc the \(75^{th}\) percentile of the concentration. The axis unit is \(ngm^{-3}\).

B. Sector plot showing the total burden of atmospheric BC\(_e\) to Svalbard. The median, 25- and 75 percentile concentrations are multiplied with the fraction of trajectories belonging to the sector in question.
Table 1. Comparison to earlier studies. The minimum, average, and maximum values and the standard deviation from each study are given in $\mu$g$l^{-1}$.

<table>
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IP - Integrating Plate method, IS - Integrating Sandwich method (Lin et al. [1973], Clarke [1982]).
Table 2. The measured apparent elemental carbon \((EC_a)\) in snow at seven field sites in Svalbard. Sampling site and its altitude, sampling date, number of samples (number of surface samples in parenthesis) together with the mean, median, minimum, maximum, and standard deviation of the concentrations are listed. Concentrations are in \(\mu g l^{-1}\).

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<td>749</td>
<td>18.04.07</td>
<td>5(4)</td>
<td>14.0</td>
<td>6.5</td>
<td>4.1</td>
<td>45.2</td>
<td>17.6</td>
</tr>
<tr>
<td>All sites except Linnebreen</td>
<td>0–1250</td>
<td>25.02.–22.04.07</td>
<td>81(48)</td>
<td>8.7</td>
<td>4.1</td>
<td>0</td>
<td>80.8</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Table 3. The median and mean for six-hour mean air \([BC_e]\) for each sector (direction of the arriving air) shown in Fig. 6. Concentrations are in ngm\(^{-3}\). The percentages of trajectories falling in to each sector are listed.

<table>
<thead>
<tr>
<th>Sector</th>
<th>% of trajectories</th>
<th>([BC_e]) median</th>
<th>([BC_e]) mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>North (N)</td>
<td>23</td>
<td>13.3</td>
<td>31.5</td>
</tr>
<tr>
<td>North-East (NE)</td>
<td>21</td>
<td>16.3</td>
<td>55.0</td>
</tr>
<tr>
<td>East (E)</td>
<td>12</td>
<td>19.5</td>
<td>80.4</td>
</tr>
<tr>
<td>South-East (SE)</td>
<td>7</td>
<td>14.7</td>
<td>97.8</td>
</tr>
<tr>
<td>South (S)</td>
<td>5</td>
<td>10.0</td>
<td>30.2</td>
</tr>
<tr>
<td>South-West (SW)</td>
<td>8</td>
<td>7.5</td>
<td>18.3</td>
</tr>
<tr>
<td>West (W)</td>
<td>10</td>
<td>10.4</td>
<td>21.7</td>
</tr>
<tr>
<td>North-West (NW)</td>
<td>15</td>
<td>13.4</td>
<td>28.0</td>
</tr>
</tbody>
</table>