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Effects of light-absorbing impurities on spectral reflectance and density of seasonally melting snow in Sodankylä, North of the Arctic Circle (SOS-2013)

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Abstract

The Soot on the Snow (SoS-2013) experiment was carried out in Sodankylä (67°22'N, 26°39'E, 179 m a.s.l.), Finland, North of the Arctic Circle, to study the effects of deposition of Black Carbon (BC), Icelandic volcanic sand and glaciogenic silt on the surface albedo, snow properties and melt of the seasonal snow. The BC was soot originating from chimneys above residential wood-burning fireplaces, except for one experimental spot with soot from a chimney of an oil burner, and another one with soot from a peat-burning power plant. The volcanic sand was a dark mixture of the volcanic ash of glaciofluvial nature, originating from under the Myrdalsjokull glacier, which may be mixed with the ash of the Eyjafjallajokull eruption in 2010 and the Grimsvotn eruption in 2011. The glaciogenic silt was lighter in colour than sand, from light-brown to slightly yellowish colour consisting mainly of silt and some coarse clay sized particles, which could be deposited on the local glaciers as well as transported over several hundreds of kilometers towards Europe. Here we present SoS-2013 results on spectral reflectance, snow density, and snow BC concentration of seasonally melting Arctic snow, two weeks after artificially applying the impurities. The BC snow albedo and snow density effects for melting snow were detected in our SoS-2013 data.

Keywords: Black carbon; volcanic sand; glaciogenic silt; soot; snow; albedo; density; Arctic.

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1. Introduction

The concentration of Black Carbon (BC) in snow may vary a lot in space and time. BC values measured in snow in Arctic Scandinavia (Tromsø, Norway) have been reported to be ~20 ppb (parts per billion which is equivalent to ng/g and µg/l meltwater) in April, although the surface concentration increased to 60 ppb in late May, during melting (Table 8 of Doherty et al., 2010). In a complementary paper by Meinander et al. (2013) for Sodankylä, Finland, north of the Arctic Circle, the BC in snow results (2009 – 2011) also suggested some increase of BC toward the late spring, and some variability from day to day, with concentrations between 9 - 106 ppb in surface snow samples (Fig. 1). For Sodankylä, the so-called "footprint" computations for the origin of BC have been presented in Meinander et al. (2013), where the modeling was performed with SILAM (System for Integrated modeLing of Atmospheric coMposition) version v5_2. (http://silam.fmi.fi). Out of 70 snow samples 10 "clean" (< 20 ppb of BC) and 12 "dirty" (> 30 ppb of BC) samples were selected, and the average footprint for both classes was calculated. Since the sizes of air-borne black carbon particles were unknown, the footprints were calculated for passive gas with no deposition, and for particles with diameter of 1.5 µm and 20 µm. The results showed that the origin of the high BC concentrations in snow were due to were due to air masses originating from the Kola Peninsula, Russia, where mining and refining industries are located.

In terms of its climate forcing, it has been estimated that BC is the second most important human emission, and only carbon dioxide is estimated to have a greater forcing (Bond et al. 2013). Deposition of BC on snow affects the snow albedo (Warren & Wiscombe, 1980; Wiscombe & Warren, 1980). The 'BC snow albedo effect' is important due to the acceleration of snow melt via the albedo feedback-mechanism. Recently, a new hypothesis on the BC snow density and melt water holding capacity effect for melting snow was published in Meinander et al. (2014) ('BC snow density effect'). The importance of this effect comes, e.g., from the fact that snow density multiplied by snow depth equals the snow water equivalent (SWE), a key parameter in many climate models.

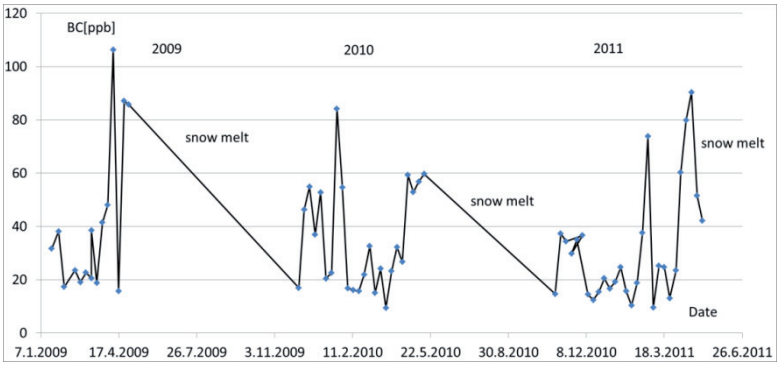

Fig. 1. The BC [ppb] in Sodankylä surface snow samples in 2009-2011, during snow season. (Data adapted and re-drawn from Table 3 of Meinander et al. (2013)).

Here we present experimental results from our Soot on Snow (SoS-2013) campaign, i.e. snow BC concentrations coupled with snow spectral reflectance and snow density, for seasonally melting snow, two weeks after artificially applying light absorbing impurities on

the snow surface. All these data are for naturally deposited snow in Sodankylä, north from the Arctic Circle.

2. Materials and methods

2.1 The SoS-2013 experiment

The Soot on the Snow (SoS-2013) experiment was carried out in Sodankylä (67°22'N, 26°39'E, 179 m a.s.l.), Finland, North of the Arctic Circle, to study the effects of deposition of Black Carbon (BC), Icelandic volcanic sand and glaciogenic silt on the surface albedo, snow properties and melt of the seasonal snow (more detailed in Svensson et al., in prep.). The experimental field was within the Sodankylä airport. The experiment was made on natural snow, and the impurities were spread only once, inside a tent chamber with the help of a blower (Fig. 2), where after the snow was left untouched and monitored until snow melt.

The volcanic sand was a dark mixture of the volcanic ash of glaciofluvial nature, originating from under the Myrdalsjokull glacier, which may be mixed with the ash of the Eyjafjallajokull eruption in 2010 and the Grimsvotn eruption in 2011. The glaciogenic silt was lighter in colour than sand, from light-brown to slightly yellowish colour consisting mainly of silt and some coarse clay sized particles, which could be deposited on the local glaciers as well as transported over several hundreds of kilometers towards Europe. The BC was soot originating from chimneys above residential wood-burning fireplaces in Helsinki, Finland, except for one experimental spot with soot from a chimney of an oil burner, and another one with soot from a peat-burning power plant.

2.2 BC analysis

Snow samples were melted in a microwave oven, and filtered through sterilized micro-quartz filters (55 mm diameter) using a hand pump attached to the filtering system to create a vacuum during filtering. Dried filters are analyzed with a Thermal/Optical Carbon Aerosol Analyzer (OC/EC) (Sunset Laboratory Inc., Forest Grove, USA) for their elemental carbon (EC) and organic (OC) concentration, following the latest protocol recommendation EUSAAR_2. The EC is used as a proxy of BC due to the thermal optical measurement technique used in this experiment.

2.3 Spectral reflectance and snow density

The spectral reflectance of melting snow was measured at SoS-2013 using two different Analytical Spectral Devices (ASD) Spectrometers, one for 325-1075 nm, and the other for 350-2500 nm. Here we report results for 325-1075 nm, for one spot of each impurity, i.e. control, soot, silt and volcanic ash. The snow densities (weight per volume) were measured manually with a snow tube (the whole snow pack) and a density cutter (for separate layers).

Fig. 2. a) Left. Soot, silt and volcanic sand were spread on natural snow in the SoS-2013 experiment in Sodankylä. b) Right. In an Icelandic dust event (Dagsson-Waldhauserova et al., in prep.) the fine silt particles, deposited on snow, formed larger grains, similarly to our SoS-2013 artificially added impurities.

3. Results and Discussion

3.1 Spectral reflectance changes due to added impurities

The Sos-2013 spectral reflectance results for the spots of reference, soot, silt and volcanic sand after two weeks of applying soot are presented in Fig 3. All these results are for melting snow with snow metamorphosis. The reflectance curves are averages for measurements on minimum of 8 different locations over the spot.

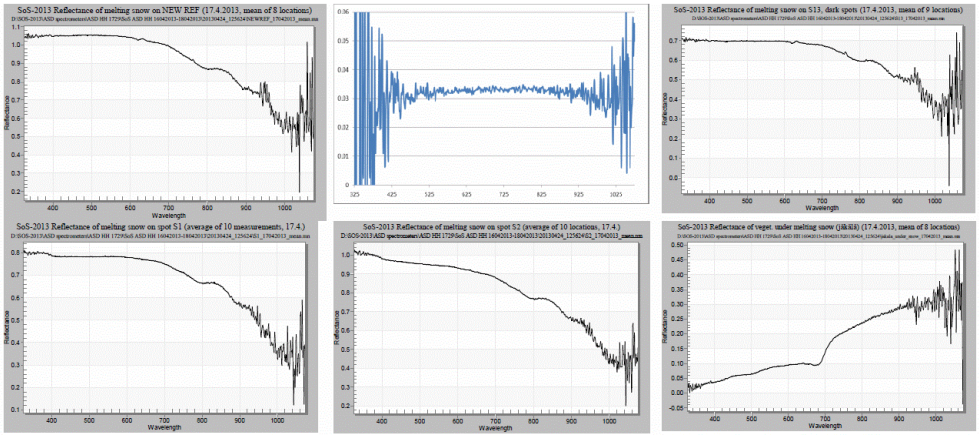

Fig. 3. SoS-2013 snow reflectance ASD spectrometer results from 17 April 2013, during snow melt, and two weeks after the artificial depositions. Up. Left: The reference spot with reflectance close to 1 at the beginning of the measurement range. Middle: The reflectance of the volcanic sand measured in the laboratory by spectroradiometer coupled with a contact probe. Right: Reflectance of the spot with volcanic sand deposited on snow. Down. Left. Wood burning soot on snow; reflectance spectrum starting around 0.8. Middle: Silt on snow, reflectance starts around 1. Right. Reflectance o vegetation under the snow spots. The results demonstrate that soot and volcanic sand reduce snow reflectance at UV and VIS more than glaciogenic silt, compared to natural reference snow.

There are several ways to analyse reflectance spectra, including calculations of derivative spectra, or various indices. On the basis of the SNICAR model (on-line version by Flanner et al. 2007), the BC in snow appears to cause increasing absorption toward shorter wavelengths (here: UV). In our data, the reference spot snow had a UV reflectance of ~ 1 (Fig. 3). This spot also contains some BC due to natural dry and wet deposition, and it could also contain artificially added impurities due to contamination from the experimental set up. The BC content for this reference snow was analysed to be 93 ppb. The UV reflectance of snow with volcanic sand (with BC on the snow, although volcanic sand does not contain BC) was 0.7, and with silt ~1. For the sooted spot, it was R(UV) = 0.8. To separate the effect of various impurities on the spectral reflectance of snow, we calculated reflectance ratios (RR) at the wavelengths of maximum absorbance (in our data UV) divided by the minimum absorbance (in our data NIR):

$$RR\ (impurity) = R(\lambda max)/R(\lambda min) = R(UV)/R(NIR) \quad (1)$$

In Fig. 4, the four cases of R(UV) are plotted versus R(NIR). We can see some indication that such simple spectral ratios could work to separate the spectral effects of the different impurities. From our SoS-2012 experiment, we have NILU-UV radiometer results, where snow albedo decreased to 0.3, for both UV and VIS (BB for 400-900 nm) wavelengths, directly after an excessive amount of soot (BC=4916 ppb in snow) was added. Prior to applying the soot, the albedo of the snow (with BC=87 ppb) was 0.9 for VIS and 0.7 for UV.

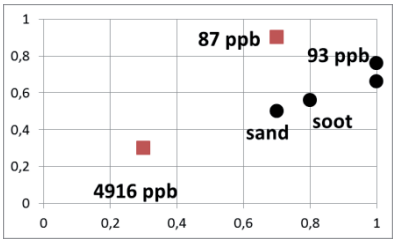

Fig. 4. The UV (x-axis) versus NIR (y-axis) snow reflectance. SoS-2013 results are marked with black circles for reference snow (BC = 93 ppb), artificially added silt, soot, and sand, two weeks after the artificial deposition. The SoS-2012 results are marked with red squares, for control snow (BC = 87 ppb) and right after the artificially added soot (BC = 4916).

3.2 Snow density effect

In SoS-2013, the added light-absorbing impurities were found to decrease the density of seasonally melting snow (Meinander et al., 2014). No relationship was found in case of non-melting snow, although an excessive amount of added BC (1465 ppb) did decrease the snow density. An independent laboratory experiment also showed that sooted snow released melt water sooner that unsooted. Three possible processes that might lead to lower snow density were suggested, too.

4. Conclusions

The impurities present at the surface of melting natural snow can be either brought there together with the snow fall, or result from dry deposition to the snow surface. In an experiment like SoS-2013, the main source of impurities is the artificial dry deposition.

This means that results of such experiments could be considered not to happen in nature, i.e., to be artifacts due to the method. However, recently, a case study of snow-dust storm in South Iceland in March 2013 showed that dust caused impurities on snow in about 200 km distance from the source (Dagsson-Waldhauserova et al., in prep.). It was also found that the fine silt particles deposited on snow formed larger grains similar to our SoS-2013 observations (Fig. 2b). Thus, experimental results of artificially deposited impurities can be considered relevant. The frequency of > 34 dust days per year in Iceland is comparable to that found in major desert areas such Mongolia and Iran (Dagsson-Waldhauserova et al., 2014). Almost half of dust events in southern part of Iceland occurred during winter or at sub-zero temperatures. Dust deposition in area of about 500,000 km^2 around Iceland was calculated as 30-40 million t per year (Arnalds et al., 2014). Deposition on the Icelandic glaciers was calculated as 4.5 million t per year with the mean deposition of 400 $gm^{-2}yr^{-1}$.

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