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Brief Communication: Light-absorbing impurities can reduce the density of melting snow

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snow with the flow, or remain in the snow. It has been shown that BC is less likely to be washed down through the snow with melt water (Conway et al., 1996; Doherty et al., 2013).

Hence, if we consider natural snow with anthropogenic BC, we can assume this impurity to remain in the melting snowpack, and not to be washed down, and to potentially cause changes in the snow properties and structure, as compared to clean snow. Therefore, we hypothesize that BC in snow might affect the liquid water retention capacity of melting snow. To test this hypothesis, we use our data of cold and melting snow, where both the snow density and BC content were measured.

2 Materials

All our snow density and BC data have been obtained for natural seasonally melting snow in Sodankylä (67°25' N, 26°35' E), Finland, north of the Arctic Circle. The data contain cases of cold and melting snow, both with and without experimentally added impurities (Table 1).

The data originate from three campaigns: the Soot on Snow experiment in 2013 (SoS-2013); the Snow Reflectance Transition Experiment (SNORTEX 2008–2010, see Meinander et al., 2013 for more details); and the SnowRadiance-campaign (SR-2009). The SoS-2013 campaign was carried out at the Sodankylä airport to study the effects of deposition of impurities on the surface reflectance and albedo and melt of seasonal snow. The experimental area was a large, flat, fenced open space, and the gravel ground was not covered with concrete or asphalt (Fig. 1). Different amounts of impurities were deposited to snow on different spots, each with diameter of 4 m, and thereafter the spots were monitored until the snow had melted. The sites were left to develop naturally, introducing as little disturbance as possible. Here we used data from three experimental spots with chimney soot, one spot with Icelandic volcanic sand (from Ólafur Arnalds⁵ and Haraldur Olafsson⁴, Iceland), and one reference spot.

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The SnowRadiance (SR) was an ESA-funded project aiming at determining snow properties from optical satellite measurements. The BC samples were collected from the snow over ice on Lake Orajärvi. The lake is frequently used in the winter, e.g., for snowmobiling.

During the SoS-2013, the SNORTEX-2009, and the SR-2009 campaigns, surface snow samples were collected for analysis of their elemental carbon (EC) and organic carbon (OC) concentrations using the filter based thermal-optical method, described and used in e.g. Forsström et al. (2009). The EC is used as a proxy of BC, due to the measurement technique used. In the SNORTEX-2010 campaign, the sampling, filtering, and laboratory spectrometer analysis followed the procedures presented in Doherty et al. (2010). Several samples were collected from each location.

The snow densities (weight per volume) were measured manually, for either the whole snowpack vertical column (the SR and SNORTEX data), or for separate horizontal snow layers (SoS data). One density measurement for each location was made. To estimate the standard deviation of the density measurement, an earlier data set of FMI was applied. Sampling of wet snow for density measurements may be difficult since liquid water easily escapes from the sampling box. Here the SoS data for melting snow was obtained for two consequent days (Table 1), before and after rainfall. The snow was then wet, but not dripping wet, and no water escape from sampling was detected.

In the SoS-2013 data, the snow hardness was classified according to the International Classification for Seasonal Snow on the Ground (Fierz et al., 2009). For any single layer of the snowpack, hand hardness index of the Hand Test corresponds to the first object that can be gently pushed into the snow: (1) very soft (fist), (2) soft (4 fingers), (3) medium (1 finger), (4) hard (pencil tip), (5) very hard (knife blade), (6) ice (ice). The snow grain sizes and shapes were estimated visually with a mm-grid, and the snow grains on the grid were also macro-photographed to allow image analysis afterwards, following the method of Fierz et al. (2009). An example of such a photo is in Meinander et al. (2008, Fig. 4).

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3 Results

In our data for non-melting natural snow from the SR-2009, SNORTEX-2009, SNORTEX-2010 and SoS-2013 campaigns, the BC concentrations varied between 8 and 126 ppb, and snow densities were 200–264 kgm⁻³. The density did not depend on the BC content (Fig. 2a, the dots inside the circle).

However, in our SoS-experiment data of 6 April 2013, the snow with the BC maximum of 1465 ppb (Fig. 2a, one data point), had the lowest density of all our data, 168 kgm⁻³. MFcr-grains (melt-freeze crust, as a result of melting and freezing) were 0.25–1.5 mm in diameter, the surface hardness value was 4 (hard snow) and the snow depth was 56 cm. For comparison, with the reference non-sooted natural snow at that time (10 April 2013) on the same experimental field: the Ppir-grains (Precipitation particles) were irregular crystals, of 0.25–0.75 mm in diameter). The BC concentration was 126 ppb, the density was 210 kgm⁻³, the hardness value was 1 (very soft snow), and the snow depth was 65 cm.

Our experimental data show that for the seasonally melting natural Arctic snow, with and without artificially added soot or volcanic ash, there was a correlation between the density and the BC content of snow (Fig. 2b). This was the case both prior to a rain period, and the next day after the rain. The densities and the corresponding BC contents were measured separately for the top 5 cm of the snow, not for the whole snow pack, and the impurities were visually observed to remain on the snow surface, too (Fig. 1). All the grains of the surface layer were melt-freeze crust (MFcr).

The BC concentrations in individual snow samples varied from 9 to 730 ppb. From these, the averages for each experimental spot were calculated (92–310 ppb), and plotted in Fig. 2b. The standard deviation (σ) for the clean reference snow samples (no added impurities) was 34 ppb ($n = 7$), and most often σ was larger for spots with added impurities, dependent on the number of samples (from 1 to 5) and the spot properties; e.g., for one spot with added soot, it was $\sigma = 28$ ppb ($n = 5$). The Eq. (1) shows the relation between the snow density ρ_s [kgm⁻³], and the BC content C_{BC} [ppb] for the

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1. *A semi-direct effect of absorbing impurities.* Absorbing impurities would cause melt and/or evaporation of the surrounding snow, resulting in air pockets around the impurities, and thus lower snow density. We have empirical observations, where impurities (both organic and inorganic) in the snow have been surrounded by air pockets.

2. *BC effecting on the adhesion between liquid water and snow grains.* If BC reduces adhesion, the liquid water holding capacity decreases. For linear warming the influence on the density of wet snow is then max 5% (at this level water flow starts in natural snow). However, with daily cycles, warm days and cold nights, the weaker adhesion may push liquid water down more day-by-day and then the influence to the density would be larger. This way also melt-freeze metamorphosis would produce less dense snow.

3. *BC effecting on the snow grain size.* Absorbing impurities would increase the melting and metamorphosis processes, resulting larger snow grains, which would lower the water retention capacity. Earlier, Yamaguchi et al. (2010) have suggested that the water retention curve of snow could be described as a function of grain size using soil physics models.

Volcanic sand is assumed not to contain BC (Dadic et al., 2013, Fig. 12a). This assumption is further supported by our own EC analysis of volcanic sand samples with the thermal–optical method showing hardly any EC. Instead, the BC in our volcanic sand spot can be assumed to originate either from long-range transport, or from our other experimental spots with added soot; carboneous material in volcanic aerosols has also been proposed to be due to tropospheric air that is entrained into the volcanic jet and plume (Andersson et al., 2013). Our observations and measurements indicate that for visually darker snow surface the analyzed BC content is larger and the measured snow density is smaller, regardless of whether soot or volcanic sand had been added to the spot.

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The significance of our results on reduction of snow density, and possibly also decreasing water holding capacity due to the black carbon, may come via the facts that (i) snow density is an important snow parameter, that has been found to correlate with several factors affecting the snow melt, such as snow age and liquid water holding capacity (Kuusisto, 1984); (ii) the snow density multiplied by the snow depth equals the important climate model parameter of snow water equivalent (SWE); and (iii) our results may have potential in reducing the uncertainties (IPCC, 2013) related to the effect of black carbon on snow melt and climate change.

In nature, the low density of new dry snow increases due to gravitational settling, wind packing, sintering, and melt-freeze events. These processes depend on the grain size, shape and organization, and snow temperature. The density of snow is also affected by water vapour diffusion in the snow pack, as well as by the temperature and the vegetation under the snow. In our experimental data, we can assume similar environmental conditions with only the impurity contents in snow being the varying factor; our results are for natural snow on natural ground, and we did not have data for drainage of melt water in the snowpack. Here we reported our first results, and more data are needed to further study the effect of light-absorbing impurities on density and water retention capacity of melting snow.

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Table 1. The origin of our Sodankylä snow density data coupled with BC analysis results. The campaigns are explained in the text.

Year	Date	Data origin	Location	Snow	BC analysis
2009	17 Mar	SR-campaign	Snow on Lake Orajärvi	Cold snow	Thermal-optical
2009	13, 19 Mar	SNORTEX	Sodankylä sites	Cold snow	Thermal-optical
2010	23, 24 Mar	SNORTEX	Sodankylä sites	Cold snow	Spectrometer (Doherty et al., 2010)
2013	6, 10 Apr	SoS-2013	Sodankylä airport	Cold snow	Thermal-optical
2013	17 Apr	SoS-2013	Sodankylä airport	Melting, before rain	Thermal-optical
	18 Apr			Melting, after rain	

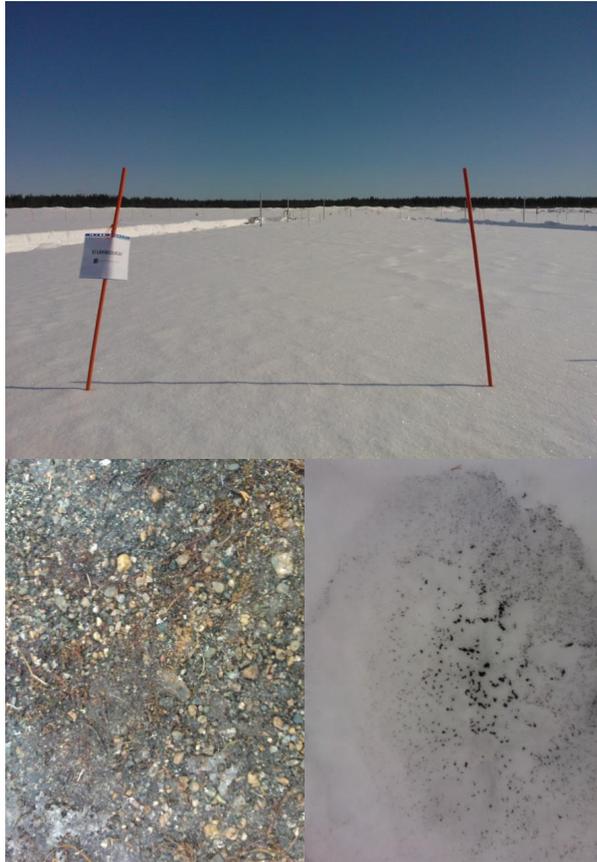


Fig. 1. The SoS-2013 experiment. **(a)** Top. The experimental field with the seasonal snow pack; **(b)** bottom left. The gravel surface under the snow; **(c)** bottom right. Artificially added impurities were visible on the surface of the melting snow.

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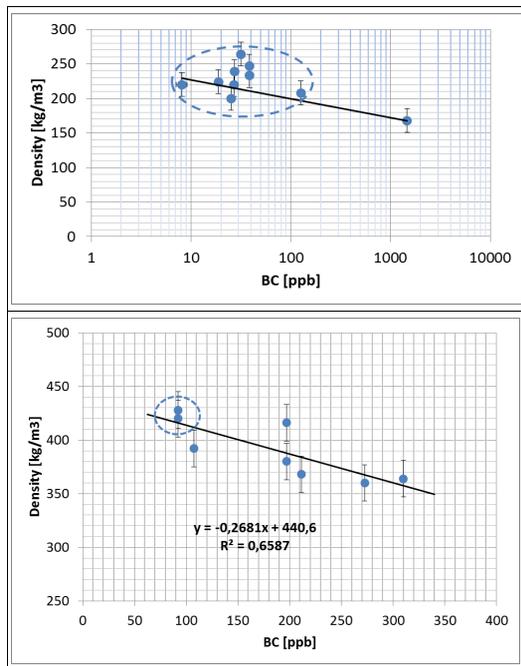


Fig. 2. The Black Carbon (BC) content [ppb] vs. density [kg m^{-3}] for the natural seasonal snow cover in Sodankylä, north of the Arctic Circle. **(a)** Cold snowpack. In natural snow (within the circle) BC concentrations were 8–126 ppb and snow densities were 200–264 kg m^{-3} . When soot was artificially deposited, the snow density decreased to 168 kg m^{-3} for a BC concentration of 1465 ppb. For the reference spot, the snow density was 210 kg m^{-3} with a soot concentration of 126 ppb. The line is the least squares linear fit through all the points. **(b)** Melting snow. SoS-2013 data for reference spots (within the circle), and spots with artificially added impurities. The densities and corresponding carbon contents were measured separately for the specified surface layers, not for the whole snow pack. The line is the least squares linear fit through all the points.