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

O. Meinander<sup>1</sup>, A. Kontu<sup>2</sup>, A. Virkkula<sup>1</sup>, A. Arola<sup>3</sup>, L. Backman<sup>1</sup>,  
P. Dagsson-Waldhauserová<sup>4,5</sup>, O. Järvinen<sup>6</sup>, T. Manninen<sup>1</sup>, J. Svensson<sup>1</sup>,  
G. de Leeuw<sup>1,6</sup>, and M. Leppäranta<sup>6</sup>

<sup>1</sup>Finnish Meteorological Institute, Helsinki, Finland

<sup>2</sup>Arctic Research Center, Finnish Meteorological Institute, Sodankylä, Finland

<sup>3</sup>Kuopio Unit, Finnish Meteorological Institute, Kuopio, Finland

<sup>4</sup>University of Iceland, Department of Physics, Reykjavik, Iceland

<sup>5</sup>Agricultural University of Iceland, Faculty of Environment, Hvanneyri, Iceland

<sup>6</sup>Department of Physics, University of Helsinki, Finland

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Correspondence to: O. Meinander (outi.meinander@fmi.fi)

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## Abstract

Climatic effects of Black Carbon (BC) deposition on snow have been proposed to result from reduced snow albedo and increased melt due to light-absorbing particles. In this study, we hypothesize that BC may decrease the liquid water retention capacity of melting snow, and present our first data, where both the snow density and elemental carbon content were measured. In our experiments, artificially added light-absorbing impurities decreased the density of seasonally melting natural snow. We also suggest three possible processes that might lead to the lower snow density.

## 1 Introduction

For seasonal snow, snow melting is an important part of the natural annual hydrological cycle. It is forced by atmospheric sensible heat flux and solar radiation, where the albedo is a critical factor due to its large variability. Snow albedo depends primarily on the grain size, wetness, impurities in the near-surface snow layer, and directional distribution of the down-welling irradiance. Deposition of anthropogenic emissions to snow cover potentially causes albedo changes. In terms of its climate forcing, black carbon (also known as light-absorbing aerosol) has been hypothesized to be the second most important human emission, and only carbon dioxide is estimated to have a greater forcing (Bond et al., 2013). The climatic effects of black carbon (BC) in snow are due to reduced snow albedo caused by absorption of solar radiation, and induced melt of darker snow, which again lowers the albedo via the albedo feedback mechanism (e.g., Warren and Wiscombe, 1980; Doherty et al., 2010).

Snow melt starts when snow temperature reaches the melting point. Then, if the heating continues, the volume of liquid water increases until the holding capacity or the saturation point of liquid water is reached. This capacity is 3–5 % on a mass basis and depends on the snow grain structure and packing (DeWalle and Rango, 2008). When the flow of melt water begins, the impurities may either be washed down through the

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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 Arnalds<sup>5</sup> and Haraldur Olafsson<sup>4</sup>, Iceland), and one reference spot.

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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<sup>-3</sup>. 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<sup>-3</sup>. 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<sup>-3</sup>, 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 ( $\sigma$ ) for the clean reference snow samples (no added impurities) was 34 ppb ( $n = 7$ ), and most often  $\sigma$  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  $\rho_s$  [kgm<sup>-3</sup>], 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; carbonaceous 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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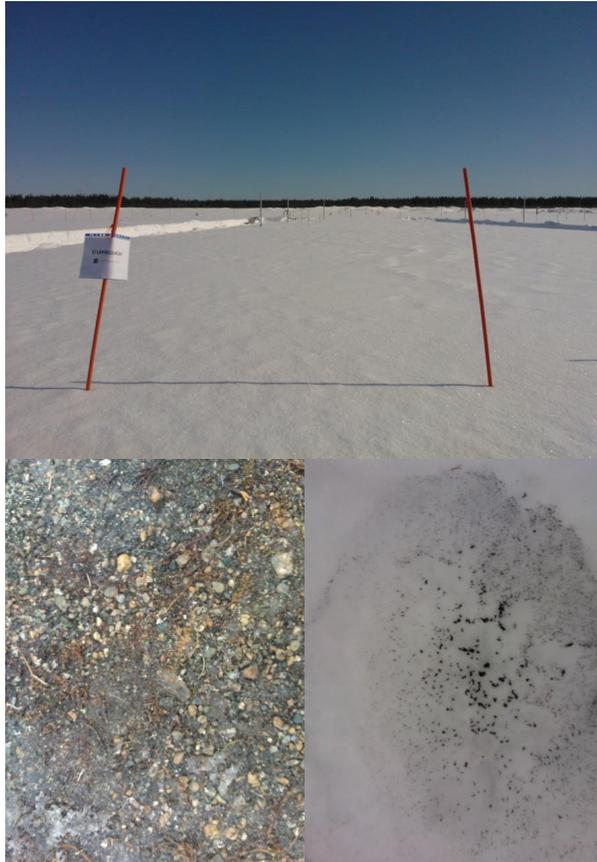
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**Table 1.** The origin of our Sodankylä snow density data coupled with BC analysis results. The campaigns are explained in the text.

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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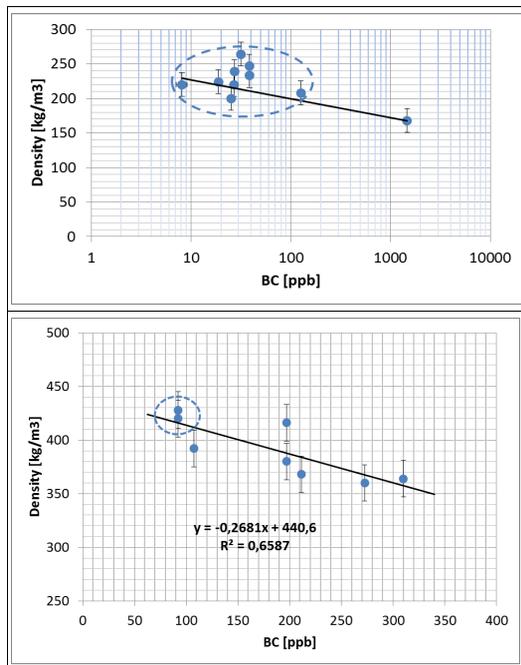
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**Fig. 2.** The Black Carbon (BC) content [ppb] vs. density [ $\text{kg m}^{-3}$ ] for the natural seasonal snow cover in Sodankylä, north of the Arctic Circle. **(a)** Cold snowpack. In natural snow (within the circle) BC concentrations were 8–126 ppb and snow densities were 200–264  $\text{kg m}^{-3}$ . When soot was artificially deposited, the snow density decreased to 168  $\text{kg m}^{-3}$  for a BC concentration of 1465 ppb. For the reference spot, the snow density was 210  $\text{kg m}^{-3}$  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.