CRAICC deliverable 8: Surface albedo changes induced by the deposition of soot to snow in the Arctic, and by the presence algae and bacteria in snow and their effect on the conversion of species (M36)

**Background**

The surface albedo of snow is wavelength dependent (see figure 1) and is influenced by many parameters. These include the snow grain size, light-absorbing impurities, snow depth, solar zenith angle, and the underlying ground's albedo. The snow grain size is the main component affecting the snow albedo. In the seasonal snowpack in the Arctic the aging process during the winter season enables the snow grains to grow naturally, as well as during spring when the onset of melt further increases the grain size. The increase in grain size has the effect of reducing the snow albedo. Light-absorbing impurities—usually airborne—are particles that when deposited onto the snow further decreases the surface albedo. Examples of light-absorbing impurities are soot, dust, and organic material. Soot, usually referenced to as black carbon (BC) in the literature, is the light-absorbing impurity with the ability to absorb the most solar radiation.

The initial change in albedo from the BC particles being deposited to the snow is only the first of a series of events that are caused by BC in the snow. The consequent effect of increased solar absorption by the BC particles elevates the snowpack temperature, which in turn enables faster snow aging and grain growth in the snowpack. This step is more important from the climatic perspective, since a known concentration of BC has a higher albedo reduction in a snowpack with larger snow grains compared to a snowpack with smaller snow grains (Warren and Wiscombe, 1980; see figure 1). An additional important feedback process is that BC particles have a tendency to stick to the surface of the snowpack (e.g. Conway et al. 1996), which further enhance the BC effect. With the BC feedback process amplifying and speeding up the onset and rate of melting of the snowpack, the underlying ground exposure adds to the snow albedo feedback in the seasonal snow environment.

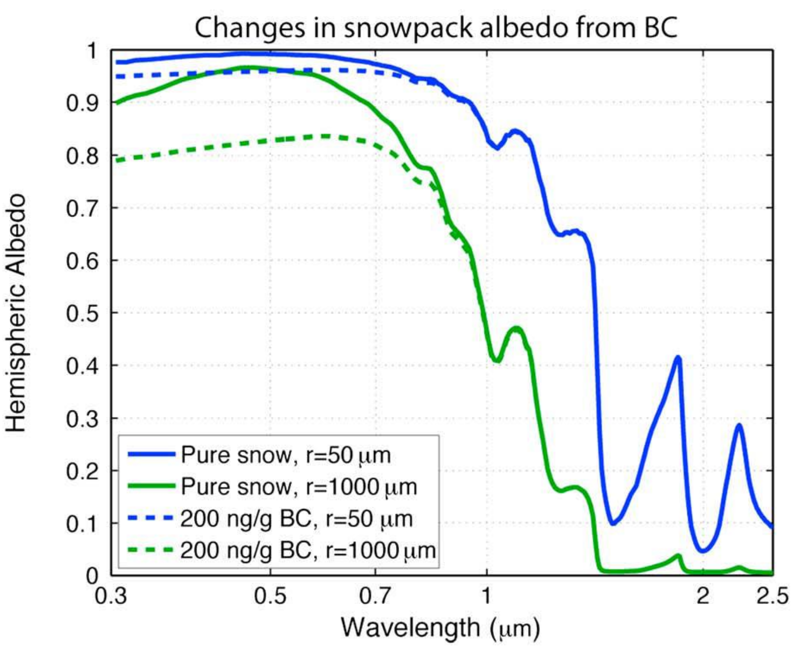


Figure 1. Albedo of snow with grain size (r) of 50 and 1000 µm, and the effect of added BC concentrations of 200 ng/g. Adopted from Bond et al. 2013

There are a few properties of the BC particles which can affect their impact on snow albedo. The mass absorption cross section of BC particles affects the amount of actual light absorption taking place in the snow. Additionally, the position of BC particles on the snow grains affects the albedo. The mass absorption cross section is affected by the size of the particles and mixing state of the BC particles with other materials, whereas the position of the BC particles depends on whether the BC particles are incorporated into the snow grains or if they are attached to the surface of the snow grains.

The albedo of the snowpack is calculated through radiative transfer calculations, with models usually presenting the radiative forcing. Several models studies have been conducted (e.g. Flanner et al. 2007; Koch et al. 2009, Rypdal et al. 2009, Skeie et al. 2011), with each model performing the calculations different.

Measurements of BC concentrations in remote areas in the northern hemisphere have shown to be on the order of 3-100 ppb according to measurements studies by Doherty et al. (2010) and Meinander et al. (2013). These BC concentrations, depending on the conditions, could yield albedo reductions of up to ~10%, which is significant in climatic forcing.

**Black carbon induced albedo changes**

Within the CRAICC framework, studies related to BC's effect of the snowpack albedo have been carried out in different regions of the Arctic.

Meinander et al. (2013) studied BC and snow albedo both with the help of SNICAR albedo model (Flanner et al. 2007) and on natural snow with BC of 87 ppb, and organic carbon 2894 (Meinander et al. 2013) and on Soot on Snow experiments (data unpublished, manuscripts in prep. by Virkkula et al.; and Meinander et al.).

During the most intensive seasonal snowmelt period of four days, we found very low albedo values. Albedo was decreasing from 0.65 to 0.45 at 330 nm, and from 0.72 to 0.53 at 450 nm. In the literature, the UV and VIS albedo for clean snow are ∼ 0.97–0.99, consistent with the extremely small absorption coefficient of ice in this spectral region. Our low albedo values were supported by two independent simultaneous broadband albedo measurements, and simulated albedo data. We explain the low albedo values to be due to (i) large snow grain sizes up to ∼3 mm in diameter; (ii) meltwater surrounding the grains and increasing the effective grain size; (iii) absorption caused by impurities in the snow.

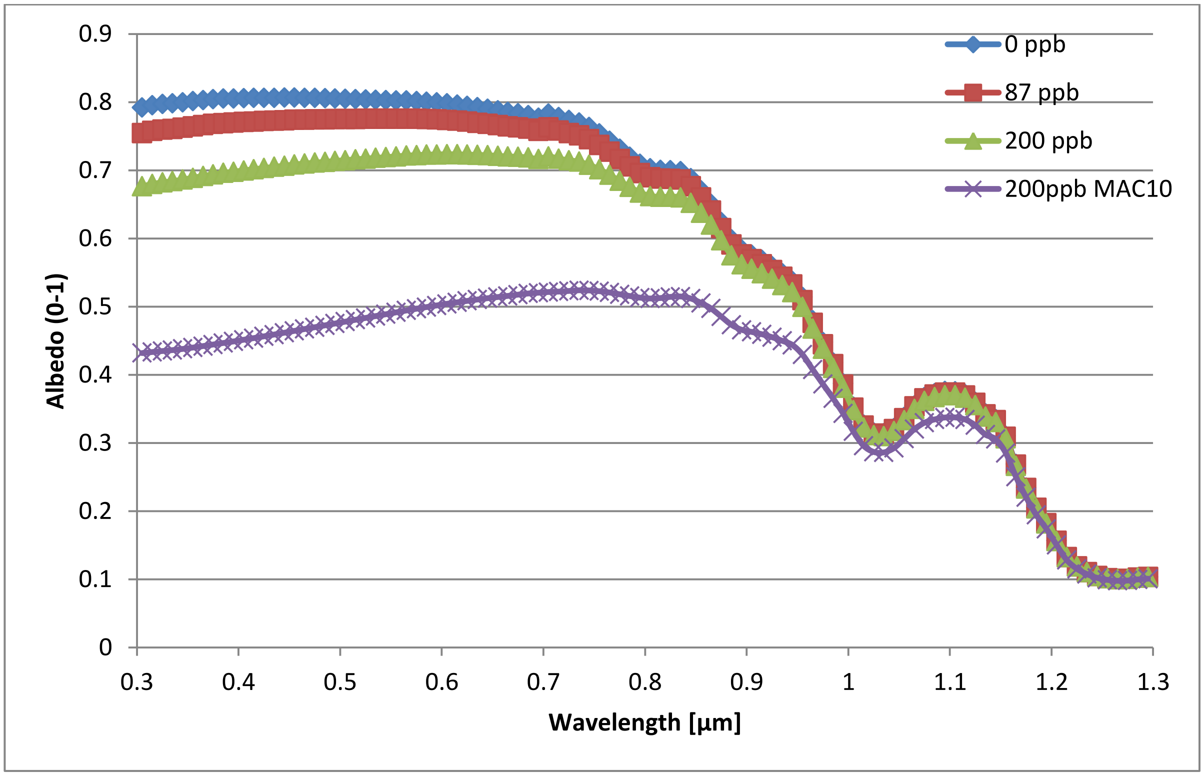


Figure 2. The SNICAR online simulated snow albedo spectra at 0.3 – 1.3 µm (clear sky at SZA = 55 degrees, grain radius 1.5 mm, snow depth 10 cm, snow density 350 kg/m$^3$) demonstrate that the absorption caused by impurities in snow is the bigger the shorter the wavelength, compared to clean snow (blue). The EC in snow determined by the thermo-optical method was 87 ppb (red). The snow BC concentration was assumed to be approximately double the EC concentration determined by the thermo-optical method (green). Introducing a mass absorption coefficient MAC=10, produced albedo values close to the lowest measured albedo of ~0.4 – 0.5 at UV (purple) (adopted from Meinander et al. (2013).

In Pallas, northwestern Finnish Lapland, BC concentrations in the surface snow has been measured to be on the order of 30 ppb (Svensson et al. 2013), resulting in a rough estimate of 2% albedo reduction in the visible-wavelengths (also using the SNICAR model). The albedo reduction is larger in melting snow, and is estimated to roughly 6%. Measurements from the CHINARE 5 (Fifth Chinese National Arctic Expedition) during 2012 from snow on the Arctic sea ice had BC concentrations in the range 2-60 ppb, which have similar albedo reductions as measurements from Pallas and measurements done by Doherty et al. (2010).

Until now, we have not studied the albedo effects due to algae or bacteria in snow, but instead we have studied i) spectral albedo changes of snow induced by deposition of soot to snow in the Arctic; Both with the help of SNICAR model and own empirical measurements, we have found that the UV part of the spectrum is most effected by the soot in snow (Meinander et al. 2013).ii) the possible effects of organic carbon in snow on snow albedo (Meinander et al. 2013); iii) the effect of BC in various snow properties related to albedo (SoS data); iv) Antarctic snow UV albedo (data unpublished, manuscript in prep. by Meinander et al.). v) variability of BC concentrations in natural Arctic snow from Arctic Scandinavia and from the Arctic Ocean; We have gained an understanding on the variability of BC in natural Arctic snow in Sodankylä (Meinander et al. 2013, Table 3). The snow BC contents, in Sodankylä snow in 2009-2011, varied in one sampling place between 9-106 ppb. vi)

The origin for the high BC concentrations in Arctic snow in Sodankylä; The high concentrations of carbon, detected by the thermal–optical method, were shown to be due to air masses originating from the Kola Peninsula, Russia, where mining and refining industries are located (Meinander et al. 2013, Fig. 9).

**References**


Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., Zender, C. S. (2013) Bounding the role of black carbon in the climate system: A scientific assessment. J. Geophys. Res. Atmos. 118, doi: 10.1002/jgrd.50171.

Conway, H., A. Gades, and C. F. Raymond (1996), Albedo of dirty snow during conditions of melt, Water Resour. Res., 32(6), 1713–1718.

Flanner, M. G., C. S. Zender, J. T. Randerson, and P. J. Rasch (2007), Present-day climate forcing and response from black carbon in snow, J. Geophys. Res., 112(D11), 202, doi:10.1029/2006JD008003.

Koch, D., Schulz, M., Kinne, S., McNaughton, C., Spackman, J. R., Balkanski, Y., Bauer, S., Berntsen, T., Bond, T. C., Boucher, O., Chin, M., Clarke, A., De Luca, N., Dentener, F., Diehl, T., Dubovik, O., Easter, R., Fahey, D. 5 W., Feichter, J., Fillmore, D., Freitag, S., Ghan, S., Ginoux, P., Gong, S., Horowitz, L., Iversen, T., Kirkev°ag, A., Klimont, Z., Kondo, Y., Krol, M., Liu, X., Miller, R., Montanaro, V., Moteki, N., Myhre, G., Penner, J. E., Perlwitz, J., Pitari, G., Reddy, S., Sahu, L., Sakamoto, H., Schuster, G., Schwarz, J. P., Seland, Ø., Stier, P., Takegawa, N., Takemura, T., Textor, C., van Aardenne, J. A., and Zhao, Y. (2009) Evaluation of black carbon estimations in global aerosol models, Atmos. Chem. Phys., 9, 9001–9026, doi:10.5194/acp-9-9001-2009.

Meinander, O., Kazadzis, S., Arola, A., Riihelä, A., Räisänen, P., Kivi, R., Kontu, A., Kouznetsov, R., Sofiev, M., Svensson, J., Suokanerva, H., Aaltonen, V., Manninen, T., Roujean, J.-L., and Hautecoeur, O. (2013) Spectral albedo of seasonal snow during intensive melt period at Sodankylä, beyond the Arctic Circle, Atmos. Chem. Phys., 13, 3793-3810, doi:10.5194/acp-13-3793-2013.

Rypdal, K., N. Rive, T. K. Berntsen, Z. Klimont, T. K. Mideksa, G.Myhre, and R. B. Skeie (2009), Costs and global impacts of black carbon abatement strategies, Tellus B, 61(4), 625–641, doi:10.1111/j.1600-0889.2009.00430.X

Skeie, R. B., Berntsen T., Myhre G., Pedersen C. A., Ström J., Gerland S., and Ogren J. A. (2011), Black carbon in the atmosphere and snow, from pre-industrial times until present, Atmos. Chem. Phys., 11, 6809–6836, doi:10.5194/acp-11-6809-2011.

Svensson, J., Ström, J., Hansson, M., Lihavainen, H., and Kerminen, V.-M. (2013) Observed metre scale horizontal variability of elemental carbon in surface snow. Environmental Research Letters, 8, 034012, doi:10.1088/1748-9326/8/3/034012.

Warren, S. G., and W. J. Wiscombe (1980), A model for the spectral albedo of snow. II: Snow containing atmospheric aerosols, J. Atmos. Sci., 37(12), 2734–2745.