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Interactive comment on "Spectral albedo of arctic snow during intensive melt period" *by* O. Meinander et al.

O. Meinander et al.

outi.meinander@fmi.fi

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Meinander O., Kazadzis S., Arola A., Riihelä A., Kivi R., Kontu A., Suokanerva H., Aaltonen V., Manninen T., Roujean J.-L., and Hautecoeur O.

To begin with, we'd like to bring out that we appreciate highly the comment given by Stephen G. Warren and Thomas C. Grenfell (University of Washington, Seattle, WA, USA).

Snow albedo is a key issue for climate change studies, in RT calculations, and satellite applications. Differences between prior published measurements and our results, pointed out by Warren and Grenfell in their comment, should not be ignored. We fully agree to their comment bringing out the fact that the prior published measurements of

albedo for clean snow in this spectral range are 0.97-0.98 (Figure 4 of Grenfell et al., 1994) and 0.98-0.99 (Figure 6 of Hudson et al., 2006); consistent with the extremely small absorption coefficient of ice in this spectral region (Warren et al., 2006; Warren and Brandt, 2008). On the other hand, our albedo results for the intensively melting European Arctic snow of Sodankylä in 2009 reveal the spectral albedos (Figure 3 of Meinander et al., 2010) for UV and visible at wavelengths of 300-560 nm to be in the range 0.5-0.7. Here a plausible explanation for our results is given, as requested by Grenfell and Warren in their comment.

The melt season. First of all, we'd like to stress the fact that our measurements represent albedo of intensively melting arctic snow, as indicated in the title of our paper, too. In the beginning of our measurement period (21 April, 2009), the melting period of this European arctic seasonal snow had already started. Hence, the albedo values of our work do not represent the albedo values of the snow accumulation period or new snow, when higher albedo values would be expected.

The grain size of the European Arctic snow at Sodankylä. Secondly, the grain sizes of Sodankylä snow are up to several millimeters. Here (Table 3 Meinander et al, 2010) the maximum grain size is reported to be 3 mm. During the SNORTEX-2009 campaign, the snow grains of various snow pits in Sodankylä have been recorded and stored by macro photography. An example of such photo is in (Figure 4, Meinander et al., 2008).

The effective grain size. We have found the melt water first to accumulate in the surface and later to move into deeper layers (Figure 5, Meinander et al., 2010). When snow melts, the effective grain size increases as water surrounds the snow grains. Hence, the effective grain size may be even bigger than the observed grain size, already up to several millimeters.

BC in snow in Sodankylä. According to the FMI Arctic Research Center's results on BC in snow in Sodankylä in 2009 (data currently unpublished), the maximum values for elemental/organic/TOT carbon were: 37.8/1734.4/1765.7 μg/l, i.e., ppb.

On albedo results during SNORTEX-2009. In our paper, we present albedo results using two independent instruments in Sodankylä during the SNORTEX-2009 campaign. Using the Bentham spectrometer on a big open field covered by snow only with no trees or bushes (place “Moomin house”), albedos at 300-560 nm are in the range of 0.5-0.7. In another smaller open field close-by (place “FMI pyranometer and UV albedo measurements”), the SL-501 broadband UV sensors measured simultaneously the erythemally weighted albedos to be in the range of 0.4-0.5. If we convert these UV albedos into 550 nm (Eq. 3 in our paper), it produces albedo estimates around 0.44-0.56 for 550 nm. These smaller albedo values are to be expected for the smaller field due to surrounding lower-albedo objects (trees, Sodankylä observatory buildings etc.). During SNORTEX-2009, additional snow albedo measurements were performed by Aku Riihelä (data unpublished). Figure1 shows his snow broadband albedo observations from three days during SNORTEX 2009. The instrument used was a Kipp & Zonen CM-14 albedometer, whose accuracy may be estimated at 5-10% relative. The instrument is sensitive to radiation on the waveband of 310-2800 nm. The observations were made at Kommattivaara (a lightly forested hill) during 20 April, at Mantovaaranaapa (completely open aapa mire) and Korppiaapa (also completely open aapa mire). Aku Riihelä’s data show that a) the broadband albedos are significantly lower than for even aged midwinter snow, implying that the melt is well under way, b) the drop in observed albedos during a single field day suggests that snow metamorphism is also very active during this time, and c) the level of the broadband albedos falls consistently during the four-day period. This behavior is consistent with an increase in effective grain size as the melt enlargens the grain size of the snowpack, and also the thinning snowpack brings more impurities closer to the surface layer where they have a greater effect on the albedo.

The CM-14 instrument was carefully leveled on a tripod and operated without breaks during the field day. All three days were effectively clear-sky, with no significant cloud disturbances on the observed irradiance. There were no obstructions in the path of the incoming Solar radiation during 22 April or 23 April 2009. Some tree shadows disturbed

the measurements on 20 April. Visual monitoring of the detector domes ensured that no frost had a chance of forming during the measurements. The effect of the equipment set-up and operator footprints on the snow albedo of the observed area have been experimentally confirmed to be no more than 0.02 during the SNORTEX campaigns (A. Riihelä, unpublished data). The instrument was mounted on a height of $\sim$ 1.5 meters, implying an observed area with a radius of 15 meters. Thus, the observed albedo may be seen as representative of the areal mean of the mire (or open woodland in the case of 20 April 2009). Hence our albedo values are supported by three independent instruments (one Bentham spectrometer, one SL-501 filter radiometer, one CM-14 albedometer) measuring during the same days at slightly different locations at Sodankylä.

Our other published snow albedo data. Earlier, we have reported erythemally weighted SL-501 radiometer snow UV albedo values for the snow accumulation period to be 0.66-0.74 in Sodankylä in 2007, in the same smaller open field (Table 3 of Meinander et al., 2008). This would mean albedo estimates of 0.74-0.84 at 550 nm. We then also reported UV albedo values of 0.5-0.7 during the melt period. We have evaluated the uncertainty of our SL-501 albedo results (when studying the SZA asymmetry) to be around 2 % (Meinander et al., 2008, Meinander et al., 2009). Moreover, we have reported Arctic UV albedo results for a more northern and cleaner location at around 87 oN to be significantly higher, i.e., mean albedo of 0.91-0.92 at UV and PAR wavelengths (Table 4 of Paatero et al., 2009) when measured using our multichannel radiometer (type NILU-UV).

Other supporting low value albedos. Perovich et al. (2002) have reported (Figure 11 of Perovich et al. 2002) for 400 nm and 600 nm albedos $\sim$ 0.7 for the Arctic Sea in August due to snow melt, while for April, they report albedos of 0.9 for Barrow Alaska (71 oN) (ref. Surface SHEBA-field experiment on Heat Budget of the Arctic Ocean at 70–80 oN, http://www.eol.ucar.edu/projects/sheba/). They explain the difference from Grenfell’s albedo value of 0.98 from South Pole (Grenfell et al. 1994) to result from the large amount of particulates present in the Barrow snow pack.

Irradiance measurement errors. There are several sources for measurement errors when measuring the solar irradiance. How ever, many of the errors are eliminated in the albedo results, when the devision of upward radiation signal to downward radiation signal is performed. This is the case when one properly leveled sensor is used, or when the up and down facing sensors have similar cosine and spectral responses. The error and uncertainty analysis of Bernhard and Seckmeyer (1999) has been our reference in use, in addition to the guidelines of the World Meteorological Organization (WMO). All the FMI owned irradiance measuring instruments are regularly checked for their angular, spectral and radiometric responses, and the required calibration procedures are carefully performed to produce reliable measurements to fulfill the WMO requirements.

The Final Outcome. As stated by Warren and Grenfell in their comment, a UV-visible albedo as low as 0.6 can be explained if the snow is large-grained and extremely dirty, for example coarse-grained melting snow (optical grain radius 1000 microns) containing 2000 ppb of black carbon (Figure 7 and Footnote 3 of Warren and Wiscombe, 1980). They continue that the black carbon values measured elsewhere in Scandinavia are only $\sim$20 ppb in April, although the surface concentration can increase to 60 ppb in late May because of concentration during melting (Table 8 of Doherty et al., 2010). Here we have given evidence that the grain radius of the European Arctic melting snow of Sodankylä may be up to several millimeters. If the effective radius is considered, the radius is even larger than that due to the melting water surrounding the snow grains. We have also shown that the black carbon concentrations in Sodankylä snow in 2009 were up to 40 ppb, and the organic carbon concentrations up to 1734 ppb. In addition, we have shown that three different independent instruments were measuring corresponding low level albedo signals during the time of research. We therefore claim that in case of intensively melting arctic snow, with melt water surrounding the several millimeter snow grains, containing possibly BC up to 40 ppb and organic carbon up to 1734 ppb, and confirmed by three independent ancillary snow albedo measurements,

the UV-VIS albedo of snow measured at an open snow covered field (surrounded by distant trees not shadowing the field during the measurement) can be around 0.5-0.7.

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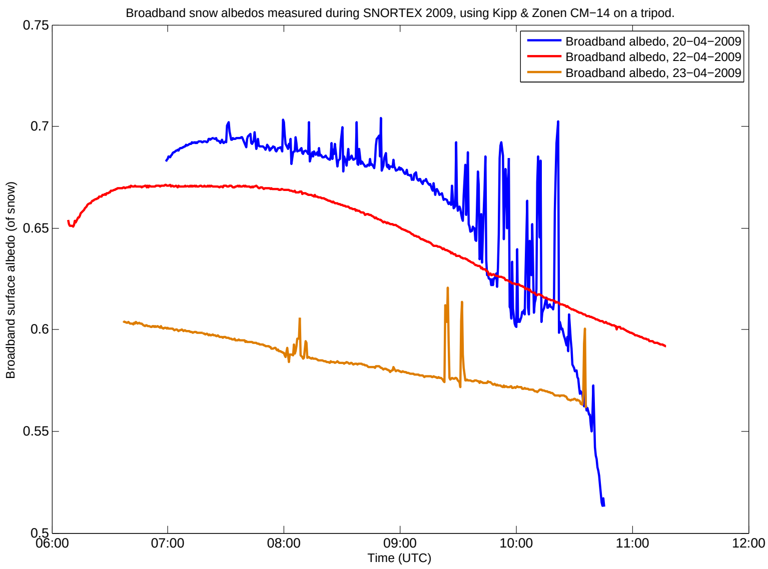

Fig. 1.