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

#### Meinander O. et al.

We would like to thank Referee #1 for presenting critical comments on our manuscript. All the comments and suggestions have been very valuable and have been taken into account in detail, as will be shown here below. Due to the Referee's comments our manuscript has truly improved.

We have earlier given the Authors' reply to the Anonymous Referee #1 General Comment #1: "A first estimate for the albedo error associated with the edge effect." by Meinander O. and Räisänen P. (<u>http://www.atmos-chem-phys-discuss.net/10/C11474/2010/acpd-10-C11474-2010-supplement.pdf</u>). Our replies to the other comments given by Referee#1 are presented here.

However, before them, we would like to bring out the fact, that due to the interactive comment given by Grenfell and Warren (http://www.atmos-chem-phys-discuss.net/10/C10240/2010/acpd-10-C10240-2010.pdf) on our manuscript, and referring to our reply to their comment (http://www.atmos-chem-phys-discuss.net/10/C10801/2010/acpd-10-C10801-2010.pdf), we have prepared the revised manuscript to include results on element carbon (black carbon) and organic carbon in the snow in Sodankylä. These were not in the original manuscript. We have also included analysis on the origin of EC/OC in the snow (introducing new co-authors Rostislav Kouznetsov and Mikhail Sofiev), and the evaluation of the snow EC/OC analysis method and results (resulting in a new co-author Jonas Svensson, from the prof. Ström group, Sweden). Furthermore, we have included the new independent albedo results first presented in our reply to Grenfell and Warren (introducing a new co-author Aku Riihelä), and new radiative calculation results on the edge effect as presented in our first reply to Referee#1 (http://www.atmos-chem-physdiscuss.net/10/C11474/2010/acpd-10-C11474-2010-supplement.pdf)(introducing a new co-author Petri Räisänen). The revised version has been prepared to give answers to all the general and detailed comments given by Grenfell and Warren, and the three Anonymous Referees, as will be shown more in detail in our replies and in the revised manuscript. Due to all these valuable comments our revised manuscript has really been improved.

#### **Referee#1 General Comments**

## /1/ The Referee comments that the size of the snow patch used for the measurements was far too small.

#### **Our reply:**

Authors' reply to the Anonymous Referee #1 General Comment #1: "A first estimate for the albedo error associated with the edge effect." by Meinander O. and Räisänen P. is presented in <a href="http://www.atmos-chem-phys-discuss.net/10/C11474/2010/acpd-10-C11474-2010-supplement.pdf">http://www.atmos-chem-phys-discuss.net/10/C11474/2010/acpd-10-C11474-2010-supplement.pdf</a>.

## /2/ The Referee comments that the duration of the campaign (4 days) was far too short to determine whether results are representative for the study area or a larger area.

#### **Our reply:**

That is correct. We fully agree. The snow melt period lasts longer (several weeks, e.g. in 2007 days 102-130, when defined as monotonical decrease of snow depth until snow was totally melted, Meinander et al. 2008, Fig. 6 and text in Chapter 3.1). We agree that our results presented in this manuscript are not representative for the whole melt period, for several years or larger area.

Our major aim with this work is to investigate the spectral behavior of intensively melting snow and not to repeat the work of Meinander et al. (2008) which deals with issues that require longer-term measurements.

We have now inserted new text where we define the intensive melt period on the basis of our snow study results (snow-ball test). Our results here are especially for an intensive melt period, as indicated in the title of the manuscript ("...during intensive melt period..."), and in the following new paragraphs, due to the general comment#2 by the Referee#1:

#### In Discussion:

"The results presented here are not representative for the whole melt period, for several years or larger areas as such. Our major aim with this work was to investigate the spectral behavior of intensively melting snow, and not to repeat the work of Meinander et al. (2008) which deals with issues that require longer-term measurements."

#### Introduction:

"In this work, the main aim was to catch the short period of the intensive snow melt with the highly accurate Bentham spectrometer setup, and study snow albedo together with key parameters of seasonally melting snow beyond the Arctic Circle."

#### Materials and methods:

"A simple "snow ball -test" was also made periodically in the Bentham albedo field. The test is in regular use in all Sodankylä snow research. This practical test tells if the properties of snow are such that one succeeds in making a snowball out of the snow on the ground. Snow balls can only be made when snow properties are suitable for making them; i.e. snow contains water but is not yet too wet. With the test, e.g., the start of snow melt can easily be detected, while corresponding snow property information would be hard to determine otherwise. "

#### **Results:**

"Between 20 – 24 April, an intensive snow melt process took place at the open field of our Bentham spectrometer albedo (Table 2). On 20 April, there was a new snow layer on the snow surface. The snow ball tests revealed that the snow was not yet melting in such extent that snow balls could be made. This was the case also the next day 21 April at 13:50 UTC. Later that day, the conditions changed. At 16:38 UTC, the snow ball test was successful. After almost 2 hours later, the snow ball test failed again. The new snow layer could still be seen on the snow surface, although it was now wet. On 22 April, the new snow layer could no longer be separated at the surface. The snow ball test was successful during the day. The melt process was under way. The snow depth (data not shown) was manually measured to change from 30 cm totally melted in some places. The automatically measured snow height at the Sodankylä AWS measurement place declined from 48 cm to 38 cm. "

#### Discussion:

"Earlier, we have also reported, for the same Sodankylä operational albedo field, erythemally weighted SL-501 radiometer snow UV albedo values of ~0.45 - 0.69 during the melt period in 2007 (Table 3 of Meinander et al., 2008). "

## /3/ The Referee comments that the spectroradiometric measurements are not consistent with broadband measurements taken only 20 m away from the primary site of study.

#### **Our reply:**

We agree that we have here a difference in the albedo values detected by our different measurement setups at different fields; ~0.5-0.7 at the Bentham field and ~0.4-0.5 at the SL-501 field.

This would mean that in the SL-501 field, either the downwelling radiation is higher than at the Bentham-field, or that the upwelling is lower.

As the sites are located only 20 m away, we can not think any other possible reason for a difference in the downwelling radiation than a possible measurement error. Therefore, we assume that the difference is due to the fact that i) at the SL-501 field the measured upwelling radiation is lower than at the Bentham.field, or ii) that we have a measurement (calibration) error. These are now discussed here.

#### i) On the possibility of the difference in upwelling radiation

We have in 2007 detected broadband albedo values during snow melt that support our 2009 spectrometer results (the new text from the Discussion of the revised manuscript, the same as in our reply#1 above ):

"Earlier, we have also reported, for the same Sodankylä operational albedo field, erythemally weighted SL-501 radiometer snow UV albedo values of ~0.45 - 0.69 during the melt period in 2007 (Table 3 of Meinander et al., 2008). "

From this it follows: Why is there a difference between 2009 broadband SL-501 intensive melt period results and the 2007 broadband SL-501 melt period results (measured at the same place with the same instrumentation)?

We start to solve this problem by checking first the 2007 results from the 2008-paper. From there, we can see that the melting snow albedo values of ~0.5-0.7 are midday averages for days ~100-120 (Meinander et al. 2008, Table 3 and Fig.9, below). In 2007, the most intensive melt period took place during the days 121-128, and then albedos decreased from 0.5 to close to 0.1 (Meinander et al. 2008, Table 3 and Fig. 10, below).



Hence, the albedo values depended on the state of melt (accumulation, melt, intensive melt, until the ground is visible and snow melted). From this it follows, that if there are open fields at different stages of snow melt, different albedo values can occur although the measurements are simultaneous. The question is if this could be the case here? Our snow height information during SNORTEX-2009 reveals that there was a difference in snow height depending on the location:

"The snow depth (data not shown) was manually measured to change from 30 cm totally melted in some places. The automatically measured snow height at the Sodankylä AWS measurement place

#### declined from 48 cm to 38 cm. "

The differences both in albedo values and in snow height measurement results would suggest that there could be spatial variability in local snow conditions and therefore in albedos, too (e.g., one field would represent the Fig. 9 of Meinander et. al (2008) albedo cases, while the other would be in the stage of Fig. 10). On the basis of this, we now update the previous chapter with new text at the end (in Discussion):

"Earlier, we have also reported, for the same Sodankylä operational albedo field, erythemally weighted SL-501 radiometer snow UV albedo values of ~0.45 - 0.69 during the melt period in 2007 (Table 3 of Meinander et al., 2008). After the melt period, the intensive melt period took place until the ground under snow became visible. During that period the albedos were lower than 0.5 (Fig. 10 of Meinander et al., 2008). Hence, the melt stage (accumulation, melt, intensive melt) of the measurement field affects the measured albedo values. If the various open snow fields are under different stages of melt, it is possible that the snow height and albedo values differ spatially even at closeby locations. Therefore it is important to have the ancillary data on snow from the same place as the albedo measurement. "

Let us still get back to the Bentham results. There the measurements were stopped when the snow was in some parts totally melted. Actually, we then measured albedo of 0.45 (the afternoon of the fourth day 24 April) at 330 nm, while the value of the same spectrum at 450 nm was 0.53 (this is written in the original manuscript). If we look at the SL-501 result from the same day (24 April) we can see that the erythemal UV-B albedo (280-320 nm) is ~0.42-0.43. These results show that there is no contradiction with the Bentham and the SL-501 albedo on 24 April, when the wavelength range is also considered. The difference lies on the previous days of intensive melt (20-23 April).

Another reason for the difference in albedo could be due to the difference in size of the measurement field and the measurement height. This can be studied in a similar way as the edge effect in our Reply#1 to the Referee#1. If we use the approach presented there with parameter values z0 = 2 m, x0 = 8 m, y0 = 8 m (as the smaller field was 16 m x 16 m), we can achieve the following results (when assuming Lambertian surface and the surrounding forest affecting only by its lower reflectance, not by shadowing):

For detecting albedo at 2m at the center of the snow field of 16 m x 16 m, the albedo of snow has a weight factor of 0.9514 (and 0.9262 if the measurement height would be 2,5 m).

These are bigger values than the values for measuring at 2,5 m on a 80 m x 50 m field 3 m away from the North edge (0.8813) indicating that if everything else were equal, the measured albedo should be higher. Hence, we can't find an explanation for the detected values here. Yet it is obvious that the size of the open field as well as the measurement height can have effect on the detected albedo results, and therefore we have inserted the following new text in Discussion:

"If simultaneous albedo values of various closeby open snowfields are at different stages of melt due to local environmental conditions (differences in size of the open area, snow height etc.), then relative changes in albedo values (e.g. in % from day to day or morning to afternoon) may offer better information on the changes in albedo during melt than the albedo values alone. This is also supported by the fact that in addition to the snow melt stage, size of the open field, and snow height, the detected albedo may also be affected by the actual measurement height."

ii) On the possibility of the measurement error in SI-501 data

We now discuss other possible reasons for the differences in the detected values. One possibility could be a measurement error in the results: are the sensors properly calibrated and leveled? The spectroradiometer set up was initially installed in order to explore relative changes of albedo spectrally due to melting of snow. The Bentham measurements were much closer to the ideal measurements set up than the broadband measurements, where the calibration was done using one constant calibration factor for each sensor. The calibration of SL-501 sensors is described more detailed in Meinander et al. (2008).

In the Meinander et al. (2008) paper it was shown that a lot of effort was put on the calibration of the SL-501 sensors in 2007, and the sensors were put to measure side by side the incoming radiation to provide empirical calibration, too. In 2009, a lot of effort was put to calibrate the Bentham measurements. Also, the primary site of investigation here was the Bentham field. Were there errors in the absolute values of the SL-501 broadband measurements, they would be minimized by using relative changes only (change in % from morning to afternoon or from day to day).

As a result of these considerations (keeping in mind the fact that in 2009 especially the Bentham measurements were performed most carefully), and due to the comment by the Referee#1, we have finally added this new paragraph in Discussion:

"The low albedo values and the diurnal decrease in albedo, first detected by the spectral data, were supported by the simultaneous broadband measurements. Bentham showed albedo values of  $\sim 0.5$  -0.7, SL-501 of  $\sim$ 0.4 - 0.5, and CM14 of  $\sim$ 0.6 - 0.75. The operational field erythemal SL-501 albedo was most often smaller than the albedo values of the primary Bentham field, or of the CM14 at the various SNORTEX sites. How ever, on 24 April, the spectral values (A = 0.45 at 330 nm and A =0.53 at 450 nm) and the erythemal UV albedo (A = -0.42 - 0.43) were close to each other. The decrease in erythemal UV albedo within a day was of ~10 %, i.e. the same as for the spectral data. Earlier, we have also reported, for the same Sodankylä operational albedo field, erythemally weighted SL-501 radiometer snow UV albedo values of ~0.45 - 0.69 during the melt period in 2007 (Table 3 of Meinander et al., 2008). After the melt period, the intensive melt period took place until the ground under snow became visible. During that period the albedos were lower than 0.5 (Fig. 10 of Meinander et al., 2008). Hence, the melt stage (accumulation, melt, intensive melt) of the measurement field affects the measured albedo values. If the various open snow fields are under different stages of melt, it is possible that the snow height and albedo values differ spatially even at closeby locations. Therefore it is important to have the ancillary data on snow from the same place as the albedo measurement. "

## /4/ The Referee comments that the changes in albedo were attributed to the solar zenith angle even though the main driver was melting snow.

#### **Our reply:**

We fully agree that the main driver was melting snow, and that is why the SZA dependent albedo signal was overdriven by the SZA asymmetric albedo, as written in the revised manuscript (in Discussion):

"Our albedo results on the melting Arctic snow showed a rapid decrease in the albedo as a function of time. Thus, our data showed some indication of possibly SZA asymmetric albedo. SZA asymmetry in albedo could also be due to surface features like sastrugi, but in our case the changes in albedo were caused by melting snow, as the forward scattering nature of snow was detected by our measurements with the Sun shining from the southern directions. Hence, the albedo decline was found to dominate over the SZA dependent albedo signal. The main driver of albedo was intensively melting snow."

## /5/ The Referee disagrees with the author's assessment that melted water moved into deeper layers over the day.

#### **Our reply:**

From the measurement data we can see the time and exact depth where the water increased or decreased. We did not make any direct water movement measurements. The argument of water movement was based on the assumption that a decrease at a certain layer together with an increase at a neighboring one due to water movement among the two. On the other hand, we agree that the snow fork measurement is also affected by such thing as snow impurities and snow grain size, hardness and density. The revised text is now:

#### Materials and methods:

#### "2.3.1 Snow depth and snow liquid water content

Snow depth was measured manually with a measurement stick in the Bentham spectral albedo field. For the measurements of snow liquid content in the same field, we used the commercially available Snow Fork by Toikka Oy (<u>www.toikkaoy.com</u>). The sensor is a steel fork that is used as a microwave resonator. The Snow Fork measures the electrical parameters: resonant frequency, attenuation, and 3-dB bandwidth. From these measurement results, the liquid water content is calculated as described in detail in Sihvola and Tiuri (1986), and Toikka (1992). In addition to the actual snow liquid water content, the snow impurities and grain sizes, hardness and density, e.g., may affect the measurement results."

#### **Results:**

"The data on snow liquid water content (Fig. 7), as a function of time and snow depth, on the same field as the Bentham measurements, showed that when the first measurement was taken (at about 7:00), the highest water content was at the deepest depth (24 cm). The changes in the water content were such that the water content started to increase in the surface layer, whereafter the surface values dropped. At the same time the concentrations in the deeper layers were first lower and increased later (Fig. 7). "

#### Discussion:

"We have also evidenced the melt water to increase in the snow surface layer of the spectral albedo field. When snow melts, the effective grain size increases as water surrounds the snow grains. From this it follows that the effective grain size may be even bigger than the observed grain size, already up to several millimeters. "

/6/ The Referee believes the observation that half-melted snow has a lower albedo than fresher snow, but refers to earlier publications [e.g. M. Blumthaler, W. Ambach, Solar UVB-Albedo of various Surfaces, Photochem. Photobiol., 48(1), 85-88, 1988], and argues on the use of the results from other researchers or climate modelers.

#### **Our reply:**

We believe that we contribute towards the improvement of the understanding on clean snow radiative properties. The contradiction to the literature on clean snow properties (as pointed out by Grenfell and Warren in their interactive comment) is a proof that more studies are needed towards such a goal.

In our revised version we have included additional analysis with the use of elemental carbon and organic carbon measurements in the snow at Sodankylä, Scandinavia. According to Doherty et al. (2010), the black carbon concentrations elsewhere in Scandinavia are lower than in our results for

Sodankylä. In addition, our data represent results on UV and VIS albedo on intensively melting seasonal snow, with big snow grains, at Sodankylä, beyond the Arctic Circle, combined with ancillary snow and environmental data. The usefulness to other researchers, and climate models, is also brought out by the fact that there are actually very few corresponding measurement results in literature. We have included the reference by Blumthaler et al. (1988) in the Reference list, and the new chapter in Introduction is:

"During melt, snow undergoes a metamorphosis process that modifies the spectral albedo (e.g., Weller 1972). The liquid water content of snow increases, and wet snow has a lower albedo than dry snow (e.g., Blumthaler and Ambach, 1988). Also, as snow ages, with or without melting, the grain size increases and therefore albedo lowers (Wiscombe and Warren, 1980)."

#### **Referee's Specific Comments**

/1/ P 27076 L13-15: The sentence is not clear. What was the value of the "regional albedo" used in the RT model? Was it the value of the locally measured albedo or something else? Was the regional albedo assumed to be constant or was it varying with wavelength?

**R:** The sentences regarding the RT calculations were clarified, with the addition of the text below:

#### Materials and methods:

"We used the Libradtran RT model (Mayer and Kylling, 2005) to calculate the up-welling and down-welling diffuse and direct spectral irradiances during a cloudless day (22 April). The measured spectral albedo (Bentham spectroradiometer data), total ozone (Sodankylä ozone sounding data, <u>http://fmiarc.fmi.fi/archive/</u>, and Brewer spectrophotometer), and aerosol properties measured with a Precision Filter Radiometer / SunPhotometer (http://litdb.fmi.fi/), were used as main inputs for the RT calculations. Our hypothesis was the following: the measured diurnal albedo change is big enough to have an impact on the solar irradiance at the surface level. The albedo values used in the RT model were the ones measured with the spectroradiometer. Solar irradiances were calculated from the RT model using the morning albedo value and were compared with irradiances that were calculated using the albedo as measured at various times during the day. A difference in irradiance in [%] between the morning and afternoon would indicate changes in radiative forcing caused by changes in albedo due to melting snow. Only relative changes were considered when comparing measurements with the model, to eliminate the effect of absolute calibration scale uncertainties of the measurement data. "

#### **Results:**

#### "3.4 RT modeling

For the clear sky day 22 April, for SZA 55-70, the spectroradiometer measured albedo minimum was  $A_{min} = 0.54$ , the maximum  $A_{max} = 0.65$  at 330 nm. The measured spectral albedo  $A(\lambda)$  was dependent of the time t. These were used as input parameter values for the RT calculations. The irradiance spectra were modeled from 6 UTC to 14 UTC to produce the spectra S1(t,  $A_{min}(L)$ ), S2(t,  $A_{max}(L)$ ), and S3(t,  $A(\lambda)$ ), where S1, S2 and S3 are the various types of modeled spectra (from 1 to 3), t is time, A is albedo,  $A_{min} = 0.54$ ,  $A_{max} = 0.65$ , L is the Lambertian assumed reflectance, and  $A(\lambda$ ,t) is the actual measured spectral albedo. Instead of the Lambertian RT model assumption of an isotropic surface (independent of the direction), the actual measured spectral albedo  $A(\lambda, t)$  is influenced by the forward-scattering nature of snow. A Lambertian albedo can still depend on wavelength. The values of the other measured input parameters for both types of RT calculations were: Ångström parameters  $\alpha = 1.253$  and  $\beta = 0.038$  (for the calculation of aerosol optical thickness  $\tau a = \beta \lambda^{-\alpha}$ ), and 347 DU for ozone. The maximum difference was observed when  $A_{max}$  was used for the model calculations, as in reality the albedo was decreasing as a function of time. For the same reason, the measured irradiance was expected to be closest to the case of  $A_{min}$ , as confirmed by our modeling results (data not shown). The differences were 2.5 - 4.5 % for wavelengths from 320 to 400 for this one day showing the 10 % change in the albedo (Fig. 9). The difference was calculated to be up to 9 % when using the results for the 4 days of the melting snow period. "

# /2/ P27078 L7: The SNORTEX-2009 campaign was very short, lasting from 20-25 April. The short duration is problematic as is not clear whether the results are representative for the site. It is also not clear whether the results can be applied to a larger region or are specific to the measurement location only. These limitations greatly reduce the value of the paper.

**R**: Please see our reply to the Referee's general Comment #2. We argue that our updated data on three instrument setups and model simulated data combined with our earlier results has the potential to solve this problem pointed out by the Referee.

The main goal of the 4 day (short) Bentham measurement campaign during SNORTEX-2009 (April period) was to investigate the spectral behavior of snow albedo in a melting snow situation. We agree that absolute albedo values can't directly be used for a larger region but since spectroradiometric measurements of snow albedo are only very few in the literature, we think that this 4 day case study provides interesting results concerning future studies of UV and VIS radiative impacts of melting snow for various applications.

/3/ P27078 L16: Please provide more details on how the quartz fiber was split and the functionality of the "internal switch". The setup uses two identical entrance optics. Ideally, albedo measurements should not depend on which of the two collectors is facing upward. Was the set up turned around during some time of the experiment? Confidence in the results could be strengthened if albedo measurements are identical regardless of the choice of the collector that is on top.

**R**: The set up that was used included two identical entrance optics. However since their transmittance can't be assumed the same (in the 1% level) we have calibrated them both separately using the same calibration unit. The instrument using each one of the input optics was calibrated inside a portable dark room, just before, in the middle and at the end of the campaign. Differences in the absolute calibration functions were within 2%. This ensures that no artificial albedos were calculated due to an instrument absolute response change (related with the input optics only), during the albedo measuring phase. In addition, at the last day of the campaign we tried to test if the albedo remains unchanged while swapping the sensors. Since during the whole campaign the albedo was changing during one day, we decided not to swap the optics for the whole day (or a few hours). So we made three tests during this day where the inputs were swapped for a short period of few minutes. Comparing the albedo values before and after, we did not find any significant change due to input optic swapping.

/4/ P27080 L13: How is "regional Lambertian albedo" defined? What albedo value was used in the model? Was it a constant value or was albedo varying with wavelength? In what way was the locally measured albedo used to determine the regional albedo? Line 23 indicates that regional albedo was based on the measured albedo minimum and maximum,  $A_{\min}$  and  $A_{\max}$ . How were these two values combined to calculate regional albedo? Was it the average or something else? I assume that there are trees, buildings, roads, etc within the radius of the measurement site relevant for regional albedo. How did these features influence the choice of the "regional" albedo value used in the model?

**R**: First, we refer to our reply to the Referee's specific comment #1, as we agree that the description

of the RT calculations needed to be clarified, as has been done now on the basis of the Referee's comments. We agree that "regional albedo" is not the correct term for this analysis, as we simply tried to calculate irradiance changes due to relative (measured) snow albedo changes. So what we have calculated is that the morning to afternoon snow albedo differences can cause a 2-4% difference in the down welling irradiance, depending on the wavelength. As an example, using satellite based albedo data for radiative transfer applications, even if satellite and ground albedo match perfectly, there will be a remaing error of the mentioned percentages caused by diurnal snow melting. Irradiances at each wavelength were calculated with the use of spectral albedo in order to include, in addition to the diurnal albedo variability, additional snow albedo spectral features.

/5/ P27081 L4: Define "UVI" (It may not be clear to all readers that UVI means UV Index).R: UV Index is now used instead UVI.

/6/ P27081 L9: In my opinion, the size of the patch of snow underneath the sensor was far too small for reliable albedo measurements. According to the text, the surface was free of snow at a distance of more than 3 meters towards the North. This translates to a nadir angle of 50°. I even consider 10 m (distance from the sensor in South, West, and East direction) not sufficient (Nadir angle 76°). Albedo was likely lower at the border of the snow patch, with effects on the measurement. The authors report that the albedo was decreasing during the course of the campaign. Since the patch of snow was so small, I hypothesize that some of the change was not caused by the change of the albedo directly underneath the sensor but by shrinking of the snow patch. This possibility should be discussed by the authors.

**R:** We refer here to: Authors' reply to the Anonymous Referee #1 General Comment #1: "A first estimate for the albedo error associated with the edge effect." by Meinander O. and Räisänen P. (<u>http://www.atmos-chem-phys-discuss.net/10/C11474/2010/acpd-10-C11474-2010-supplement.pdf</u>). (If some of the albedo change was not caused by the change of the albedo directly underneath the sensor but by shrinking of the snow patch, this possibility would be proportional to the size of the open area.)

#### /7/ P27080 L22: Please provide a reference for these "semi-empirical equations."

R: References now provided: Sihvola and Tiuri (1986), and Toikka (1992).

# /8/ P27081 L18: Why wasn't the "2 min time step" used throughout? During 6 minutes, the solar zenith angle changes appreciably, with effects on radiation levels also during clear skies, in particular at short wavelengths.

**R**: Here, a 6 minute time step was used for clear sky conditions (first 2 days), and 2 minute step was elaborated for variable cloudiness (last two days). 6 minute-time-step was easily interpolated in one minute values and introduces less uncertainty at (low SZA and low wavelengths) low irradiance measurement levels. For cloudy conditions the two minute step was necessary to capture sudden irradiance changes due to clouds.

/9/ P27082 L1+: Is it sensible to parameterize albedo as a function of SZA when the dominant driver of albedo change is not SZA but the melting of snow? Also, Figure 2 shows that that albedo is declining on every day as a function of time. In the morning, SZA is decreasing with time and in the afternoon SZA is increasing with time. The difference (SZA-SZA\_min) of Eq. (1) is therefore always positive. In the morning, A is larger than A\_midday, so the coefficient c should be positive, not negative (c = -0.0024). In very cold environments, where the snow does not melt or change its morphology during the course of a day, it is conceivable that albedo depends on SZA, which means that surface reflectance is not isotropic (i.e. the albedo is not

# Lambertian). With the data presented by the author, I think it is not possible to decouple changes in albedo due to non-Lambertian reflectance from changes in albedo caused by melting snow.

**R**: In the revised version we have removed the SZA equation as our focus on the revised version is on the spectral albedo values and the impurity concentrations. We are interested in the rate of the albedo decrease and also to investigate if this rate is different for different wavelengths. We have now calculated the albedo change per hour for both UV and VIS for day  $22^{nd}$ .

/10/ P27082 L7: Given albedo with a precision of 6 digits is unreasonable considering the measurement uncertainty. Also, according to Eq. (1), c = [A(06:00) - A(10:00)] / [68.9-55.38)]. According to Figure 2, A(06:00) is larger than A(10:00)], not smaller as in printed in the equation in line 8.

**R:** We agree and this is now corrected, we also refer to our reply on #9 above.

## /11/ P27082 Eq. (3): R<sup>2</sup> is only 0.6, indicating that a linear model is not a good method to calculate albedo in the visible from albedo at 310 nm.

**R:** We agree to this, and a new sentence is included in Discussion:

"In our data, when calculating albedo in the visible from albedo at 310 nm,  $R^2$  was only 0.6, indicating that in these data (snow with large snow grains and containing impurities) a linear model was not as good method as for UVA conversion from UVB ( $R^2 = 0.97$ ). "

/12/ P27082 L22+: How small was the "other smaller field close by?" How large was the patch of snow on that field? Figures 3 and 4: The product of the solar spectrum and the responsivity of an instrument measuring erythemal irradiance, such as SL501, peaks at about 313 nm. The albedo measured with the SL501 should therefore match the albedo measured at 310 - 320 nm with the Bentham spectroradiometer. On 22 April, the albedo at 313 nm measured with the Bentham was about 0.55 (Figure 3). On the same day, the albedo measured with the SL501 was about 0.45 (Figure 4). What is the reason for this discrepancy? Is it perhaps the different sizes of the snow patches at the two locations? This discrepancy further deteriorates my confidence in the albedo measurements presented by the authors.

**R**: We disagree, and refer here to our replies due to the Referee's general comments 1, 2 and 3.

/13/ P27083 L7: I cannot discern from Figure 5 that "after several hours of accumulation, the water moved into deeper layers". To me, Figure 5 only snows that there is a tendency of increase in liquid water content as function of time, regardless of depth. For example, when the first measurement was taken (at about 7:00), the highest water content was at the deepest depth (24 cm), contrary to the statement of the authors.

**R**: We agree, and we have answered this in our reply to The General comment #6 (here above).

/14/ P27083 L10: Snow grain sizes changed from 0.25 mm to up to several millimeters. According to Section 2.3., grain size was estimated visually with a mm-grid. I think it is not possible to accurately determine a grain size of 0.25 mm visually with a mm-grid, even with a magnifying glass. How was it really done?

**R**: We agree that this needs to be clarified. The following new sentences have been included in Materials and Methods:

"The temporal changes in the snow grain sizes and shapes, according to Fierz et al. (2009), were estimated both visually with a mm-grid, and the snow grains on the grid were also macro-photographed to allow image analysis afterwoods. An example of such a photo is in Meinander et al. (2008, Fig.4)."

# /15/ P27083 L21: I think there is some confusion on the meaning of "Lambertian." Lambertian means that the radiance of the snow surface is isotropic, i.e. independent of the direction. A Lambertian albedo can still depend on wavelength. So it seems that both types of calculations performed assumed Lambertian albedo. The albedo used for the first type was independent of wavelength, while that used for the second type was not.

**R**: The measured spectra used as input results from the forward scattering nature of the snow. A clarified description is given here in our reply to Referee's specific comment #1.

# /16/ P27084 L11: As already stated above, SZA is not the driver of the albedo change observed over any given day. With the author's experiment, changes in albedo due to the non-Lambertian nature of the snow reflectance cannot be decoupled from changes caused by melting snow.

**R:** We agree that all conclusions provided in this work are based on the assumption of the Lambertian albedo. However, since both 2pi sensors were located at the North edge of the open field, and thus the forward scattering nature of the snow was always detected with our measurements (the Sun was shining from the southern directions for SZA 55-70 degrees). Based on this fact, non-Lambertian albedo could not introduce the diurnal albedo pattern that was calculated during this campaign.

#### /17/ P27084 L13-22: The SZA-dependence of albedo in Antarctica has a different cause than the apparent change of albedo with SZA at the study site in Finland. Without having read the paper by Pirazzini, I assume that changes in albedo with SZA observed in Antarctica are related to the non-Lambertian character of snow reflectance. If a snow surface does not have any preferred orientation (e.g. no structures formed by the prevailing wind such as sastrugi), changes in albedo should only depend on SZA, not on the solar azimuth angle, and should therefore be identical in the morning and afternoon. That is not the case at the Finland site.

**R:** In the revised version, we focus on the spectral albedo values and the impurities on the snow, and therefore we have removed the SZA equations and the discussion on the SZA dependency. The new text in Discussion:

"Thus, our data showed some indication of possibly SZA asymmetric albedo. SZA asymmetry in albedo could also be due to surface features like sastrugi, but in our case the changes in albedo were caused by melting snow, as the forward scattering nature of snow was detected by our measurements with the Sun shining from the southern directions. Hence, the albedo decline was found to dominate over the SZA dependent albedo signal. The main driver of albedo was intensively melting snow."

/18/ P27085 L20+: The relationship of albedo at UV-B, UV-A and visible wavelengths established by the authors (Eqs. (2) and (3)) is likely not universal. So I don't see how these relationships can help to "achieve as accurate albedo estimates as possible" (L20), which could be used as input to climate models.

**R**: The Referee is right. We fully agree that the relationships of VIS, UV-A and UV-B are not to be used "to achieve as accurate albedo estimates as possible, which could be used as input to climate models". In fact, that was not our goal in the original manuscript and that is not the goal in the revised version of our manuscript. To clarify this more, we have included new chapters on the importance of albedo estimates in the Discussion:

"A variety of climatological studies including radiative forcing of the planet are dependent on snow albedo assumptions at given seasons. For melting snow seasons these assumptions have to be very carefully implemented in various modeling codes. Also, during snow melt, the effective surface UV albedo distributions (like presented in Tanskanen and Manninen (2007), and Robinson and Kukla (1984)) are expected to move toward smaller values. We may expect that snow height dependent parameterizations (like in Arola et al., 2003), in turn, might function well during melt time. Winther (1993) has presented the progress of snow albedo for a Norwegian research site, where the albedo decreased as the snow went under a process of metamorphosis. Snow albedo was first determined as a function of temperature index alone. An improved accuracy of 2 - 6 % in estimated snow albedo was obtained when solar radiation was included. In several models, such as CAM 3.0 (Collins et al., 2004), ECHAM5 (Roeckner et al., 2003; Roesch and Roeckner, 2006), and in the ECWMF model (ECWMF, 2010) snow albedo decreases with temperature (either linearly or exponentially). The basic parameterizations have the potential to be improved. According to Pedersen and Winther (2005), snow depth-dependent parameterizations perform better during the snowmelt period than temperature-dependent parameterizations. In the paper by Cheng et al. (2006) it has been shown, that in the case that the albedo parameterization is too sensitive to surface temperature, errors in the surface energy and mass balance grow rapidly due to the strong positive feedback between albedo and temperature errors. Furthermore, according to Pirazzini (2008), the representation of the snow and ice albedo for climate and numerical weather prediction models may be one of the most serious oversimplifications, and this may cause large errors in weather prediction and climate simulations. Pirazzini (2008) has presented a simulation experiment with the two-dimensional mesoscale model of the University of Helsinki, Finland, where the old snow albedo of 0.7 was used instead the measured albedo of 0.83 (fresh snow). They concluded that in the case of fresh snow, the use of old snow albedo and thermodynamic values caused, alone, a delay in the surface cooling, and about 3 °C of error in the surface temperature. Therefore, we might expect that the differences in snow albedo during melt with variation from appr. 0.8 to 0.4 in our results might cause a significant effect, too. "

#### **Typos**

P 27076 L22: Change "have effect" to have an effect" **R:** Corrected.

P 27076 L12: Delete "monochromator" after "150 mm" **R:** Corrected.

P27079 L2: . . .showing deviations of less than +/-1% for the entire spectral range based on measurements of the three lamps used for the calibration procedure. **R:** Corrected.

P27079 L6: Replace "above another field at  $\sim$ 20 m distance" with "which were located 20 m away from the site of the spectroradiometric measurements." **R:** Corrected.

P27079 L14: Delete "at the wavelengths of UVB (280-310)" The SL501 resembles the

action spectrum from erythema, which has also a contribution from the UV-A. **R:** Corrected.

P27080 L15+: . . .in the morning and afternoon would indicate changes in radiative forcing caused by changes in albedo due to melting snow. Only relative changes were considered when comparing the measurements with the model. . . **R:** Corrected.

P27080 L19: Change "Absolute calibration scale" to " The absolute . . ." **R:** Corrected.

P27082 L9: Change "at one time" to "at any given time" **R:** Corrected.

P27083 L24: Change "for the both" to "for both" **R:** Corrected.

P27084 L2: Change "was to appear" to " was observed when A\_max was used for the model calculations **R:** Corrected.