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 the Referee#2 for presenting comments and suggestions, which have greatly improved our manuscript. Here we give our reply to the Referee’s comments.

Before that, 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-phys-discuss.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#2 General Comments

1.” I am missing an introduction which gives a qualitative explanation, based on literature and snow RT models, of the factors and their importance for modifying the spectral albedo during the melting process (eg. Wiscombe and Warren, or Pirazzini, Arola et al in the reference list). Factors to be mentioned: metamorphosis process, snow-ice-water suspension, grain size, extinction, wavelength dependence, snow depth vs albedo of the underlaying ground. Then, in the discussion part, Chapter 4, the relevance of ancillary data and other factors affecting the extinction of radiation from a melting snow pack could be discussed, which potentially could explain why eg.the observed albedo is lower than in Antarctic studies.”

Our reply:

We have followed the suggestion by the Refreree#2. As a result, the following new paragraphs were included in Introduction and Discussion:

Introduction:

“The measured albedo is determined by the target’s basic properties and the overall environment around the target. According to literature (Wiscombe and Warren, 1980; Warren and Wiscombe, 1980), and RT models (Flanner et al., 2007; Gardner and Sharp, 2010; Mayer and Kylling, 2005), the effective snow grain size; i.e. grain size and shape distributions, or specific surface area (Domine et al., 2007); is the most important factor to determine snow albedo. According to theory

(Wiscombe and Warren, 1980), snow albedo decreases as the grain size increases, as a smaller effective radius increases the probability that an incident photon will scatter out of the snowpack (Gardner and Sharp, 2010). Other important snow properties include the liquid water content; the concentration of absorbing inorganic and organic impurities in the snow; as well as their vertical distribution in the snowpack together with snow depth and albedo of the underlying ground. 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).
In turn, the key environmental factor is the solar illumination (direct and diffuse irradiance), depending on the solar zenith angle (SZA), cloud cover, and atmospheric composition (Flanner et al., 2007; Mayer and Kylling, 2005). Albedo increases as the solar elevation decreases, i.e., albedo is SZA dependent (e.g. Fig. 4 of Gardner and Sharp, 2010), because at higher angles of incidence a photon will, on average, travel a path that is closer to the surface increasing its probability of experiencing a scattering event that will send it out of the snowpack. In addition, albedo is a scale dependent variable, but can be measured at any selected height. The operational meteorological local albedo is defined to be measured at a standard height of 1 - 2 m (WMO, 2008, p. I.7–19). Albedo measurements are influenced not only by the local snow albedo underneath the measuring radiometers, but also the combination of low-albedo and high-albedo surfaces within a larger radius. Therefore an effective albedo is often defined to describe the net effect of the albedo, as derived by comparison with a model, (Schwander et al., 1999; Kylling et al., 2000; Bernhard et al., 2007). Finally, the ability of detecting accurately the albedo of a surface depends on the measurement uncertainties and errors introduced by the measuring systems (e.g., Bernhard and Seckmeyer, 1999).”

Discussion:
...“We have presented spectral and broadband UV and VIS albedo results on seasonal intensively melting snow at Sodankylä, beyond the Arctic Circle. 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 (Wiscombe and Warren, 1980; Warren et al., 2006; Warren and Brandt, 2008). On the contrary, our albedo results reveal spectral albedo for UV and visible, at wavelengths of 300 - 560 nm, for SZA 55 - 70 degrees, and for clear sky and cloudy sky, to be in the range ~0.5 - 0.7. These low albedo results are supported by three simultaneous independent albedo measurement setups (one Bentham spectrometer, one SL-501 filter radiometer, one CM-14 albedometer) measuring during the same days at slightly different locations at Sodankylä, as well as by simulated albedo data using SNICAR-online (Flanner et al., 2007) with realistic large snow grains (3 mm diameter) and black carbon (87 ppb). We have also measured previously UV albedos of 0.5 - 0.7 for melting snow at Sodankylä (Meinander et al., 2008). Here a plausible explanation explanation for our low albedo results is given and discussed.“... (whereafter a longer discussion follows).

2. “The results of ancillary data, which potentially aids explaining the albedo observations (grain size, temperature and liquid water profiles, Figure 5, 6) looks separated from the interpretation of albedo variations (Figure 2, 3). To give some clues for discussion: Could it be that the snow pack of melting snow was optically thin due to large grain size, so the low-albedo ground underneath the snow is ’seen’? Eg. in Wiscombes work, 1000 micron grain size would correspond to a liquid-equivalent depth for which the snow pack becomes semi-infinite, to be 50 cm of old melting snow. How is this in relation to the Arctic study, where grain size is even bigger and the snow depth was gradually diminishing to zero (20 cm in Figure 6). How is

this related to Arola's work on satellite reflectivity versus snow depth (Figure 1 in their paper), where apparently the reflectivity of a 0.02 m (2 cm) snow depth is marginally different from a 0.1 m thick snow pack? What is the importance of the surface layer compared with the layer beneath? Looking at Figure 5 in Meinander's study, where the liquid water content of the 0 cm surface layer was very low in the afternoon, and completely wet all the way below, could this observation aid the interpretation of Figure 2, 3, 7? Further, melting leads to radiation entering deeper into the snowpack, where radiation may become effectively trapped if snow is polluted. Looking at Figure 3, UV is relatively more attenuated than visible from 9 to 11 UTC. Does this indicate absorbtive extinction? Effect of debris from nearby trees?"

Our reply:
We fully agree with the Referee's comment. In the revised version the ancillary data is used to explain the detected albedo values (we refer also to our Reply#1 to the Referee's General comment #1 here above), and also by including the ancillary measurement data as parameter values for the simulated albedo data:

Results
"The simulated albedo data were calculated using the SNICAR-online version with our measurement results as input data for clear sky (22 April, intensive melting) and diffuse sky (24 April, snow almost melted). To simulate the lowest possible albedo due to the effect of SZA, the value of SZA=55 degrees was used, as it was the SZA minimum value for midday on 22 April, at one degree accuracy. We used the following realistic input values (otherwise model default values applied): a) clear sky case: snow depth of 10 cm, snow grain size radius 1.5 mm, hydrophobic or hydrophilic black carbon of 87 ppb; b) diffuse sky case: snow depth 5, snow grain radius 1.5 mm, hydrophobic or hydrophilic black carbon black carbon of 87 ppb. A snow density value of 350 g/m3 was used referring to Kuusisto (1984).
From these, the clear sky simulated albedo (Fig. 11) with 10 cm snow depth and 350 g/m3 snow density, produced broadband A = 0.58 (for both the hydrophobic and hydrophilic BC). The spectral albedo values for wavelengths 300 – 400 nm were A < 0.77 and A < 0.76, accordingly. In turn, for diffuse sky with 5 cm snow and 350 g/m3 density, the broadband albedo was A = 0.58 for hydrophobic BC, and A = 0.56 for hydrophilic BC. The spectral albedo values for wavelengths 300 - 400 nm were A < 0.69, and A < 0.68, accordingly. These albedo values were based on the snow analysis result of EC = 87 ppb, determined by the thermo-optical method (discussed further in Chapter 4.4)."

3. "Spectral albedo in UV is higher than measured with the two SL-501s. Could it be that the results are not comparable due to different fields? Ratio of area covered by trees and buildings to area of snow-free land? Has the measurements with the SL-501 been cosine-corrected? Different distributions of up- and down-welling radiance may require different cosine corrections of the two meters."

Our reply:
We agree that the difference in the albedo values detected by our different measurement setups can be due different fields as noted by the Referee. The cosine correction point presented by the Referee is now included in the Discussion, too. Due to these comments by the Referee#2, we have added new text 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 ~0.5 - 0.7, SL-501 of ~0.4 - 0.5, and CM14 of ~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. However, 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. The independent broadband CM14 albedo data showed that a) the broadband albedos were lower than for even aged midwinter snow (measured during SNORTEX experiments), implying that the melt was well under way, b) the drop in observed albedos during a single field day suggests that snow metamorphism was also very active during this time, and c) the level of the broadband albedos falled 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."

"In addition, the calibration factor of the broadband SL-instruments could be improved (as described earlier in Meinander et al. 2008), and different distributions of up- and down-welling radiance might even require different cosine corrections of the two meters. Yet, the most important fact of our results remains: all these measurement results showed albedo values lower than those presented in literature for clean snow."

4. "Many of the references cited looks superficially linked to the results and discussion, as they were put in at last, without really going into a discussion of these results. Examples: Page 11, line 12, it is said 'The increase in snow albedo is in accordance with theory', without giving the reader a clue of the theory or which reference to find. Or on page 12, line 7-8, the reference to Wiscombe and Warren is in the context of smaller grain size of this Antarctic study compared with the Arctic study. But this study is highly relevant for the interpretation of the Arctic results, as all factors studied by theory may be related to Figure 2 and particularly Figure 3."

Our reply:
Yes, we agree with the Referee's comment. In our reply here to the Referee's comment #4, we refer to our replies on the Referee#2 general comments #1 and #2 here above, where we show how we have changed our revised manuscript for interpretation of our results.

5. "The parameterization of a linear relation to SZA-difference may not be of general use for other sites. The air temperature reached almost +10_C in the core-period 22-24 April, which may have had a much stronger effect on the melting process and albedo changes than the radiation energy absorbed. Further, the albedo in the visible is poorly correlated with the UVB albedo (equation 3). In addition to this, the formula is based on the midday albedo of the day, which differs from day to day. The authors suggest including environmental parameters in the parameterization, but which would require a larger data set. If this could be worked out and validated, it would be a really valuable contribution."

Our reply:
We agree with the Referee’s comment, and 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 also agree that in our study the visible correlates poorly to UVB, and this is commented in the revised manuscript Discussion, too:

“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 (*$R^2 = 0.97$*).”*

6. The SNORTEX experiment is within the framework of satellite application facilities. It would be interesting how the ground measured albedo corresponds to satellite observations for the same are, using e.g. OMI data.

Our reply: We fully agree but this was not the scope of this paper. It may be a subject of a future paper, and also a paper by other SNORTEX participants.

Referee’s Specific Comments

1. **Abstract and in the last paragraph of the Discussion section: The sentence says that ’. . . showed a wavelength dependent difference between the modeled and the measured radiation by up to 9 %’. On page 10 and Figure 7, what is shown is 2.5 and 4.5 % for the 22 April, whereas the total change for the 4 days of melting snow is said by words to be 9 %. Inclusion of a new Figure for the 4 days period, or extending Figure 7 may be helpful.**

R: We agree to the Referee’s comment that it would be helpful to clarify these RT results. With these RT calculations, our main research question was: How much does the detected 10 % daily decline in albedo effect on the calculated irradiance? Our result was that the morning-to-afternoon snow albedo differences can cause a 2 – 4 % difference in the downwelling irradiance, depending on the wavelength. 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. As the daily albedo values were higher in the morning than in the afternoon of the previous day, it is obvious that the total effect on irradiance during 4 days is smaller than the effect for a single day multiplied by the number of days (here it was calculated that during 4 days the difference in irradiances were up to 9 %). What do these RT results mean? 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. As the key question is the effect due to the daily 10 % albedo decline, we suggest to clarify the contents, to remove the 4 days irradiance results from the revised manuscript, and to keep Fig.7, and then the revised results and discussion are:

Results:
“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.“*

Discussion:
“We also found, that the albedo of melting snow also decreased by ~10 % as a function of time within a single day, asymmetrically to SZA. In the mornings, the albedo signal was slightly higher than it had been the previous evening, possibly due to frost conditions during the night time. Here, the bottom surface (24 cm) had liquid water, and a temperature profile close to melting conditions (0 ^{o}C), suggests that water vapour from the ground could possibly enter the snow surface layer, forming ice crust. The ice crust could then affect the albedo by increasing albedo when icy, and decreasing albedo when melting from the surface. The RT calculations showed that if this 10 % daily melt time asymmetry effect is ignored, an error of ~2 - 4 % in the calculated clear sky downward irradiance is made for one day. This would mean, e.g., that if using daily satellite based albedo data for radiative transfer applications, even if satellite and ground albedo were to match perfectly, there would be a remaining error of the mentioned percentages caused by diurnal snow melting.”

2. **Introduction, page 3: I recommend restructuring this section, so that the scope of this investigation is listed at the end, and the ’how to do’ paragraph (lines 24-29) moved to Materials and method’s introduction part. The aims in 2.4 RT model calculations, page 6 (model to measured comparison) should be moved to the aims-part of the Introduction for easier readability, so all aims are collected from the beginning.**

R: We have followed the Referee’s suggestion. The scope is now at the end of the Introduction, and how-to is in the beginning of Materials and methods:

Introduction:
“In this work, the main aim was to catch the short period of the most 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. The snow albedo measurements were made at Sodankylä (67^{o}22’N, 26^{o}39’E), belonging to the northern boreal forest zone with the snow type of taiga. Our main focus was on spectral albedo, combined with broadband up-welling and down-welling radiation measurements, various ancillary environmental data, and with the modeling of diffuse and direct spectral irradiance and snow albedo. In RT calculations, the aim was to study how big effect (error) would a measured realistic change in diurnal albedo values cause on the modeled irradiance, if the observed diurnal albedo change of melting snow is ignored. In addition, RT calculations were performed to get an estimate of the edge effect (forest surrounding an open field) on the detected albedo. In albedo simulations, our aim was to study if the simulated data agree with the measured albedo, when the known big snow grain sizes of melting snow, and measured Sodankylä snow impurity concentrations of elemental and organic carbon were applied. For the purpose of this study, elemental carbon is used synonymously with black carbon due to their measurement technique dependence in snow impurity studies. Our aim was also to show why our snow impurity concentrations, analyzed with the thermal-optical method, were higher than expected when compared to Doherty et al. (2010).”

Materials and methods:
“For the albedo measurements, a Bentham-spectrometer setup with two entrance optics, as well as broadband UV SL-501 radiometers and CM-14 albedometers, performed irradiance measurements during the Snow Reflectance Transition Experiment SNORTEX-2009. For investigating the effect of snow albedo on the modeled irradiance, we used the Libradtran RT model (Mayer and Kylling, 2005), with our measurement data as model input. For the albedo simulations we utilized the SNICAR on-line version (Flanner et al., 2007) with our measured snow data as model input.”

3. “ Ancillary measurements, page 5 and 6. How is the ’complex dielectric constant’ related to snow water liquid content and density of snow? And how is the semiempirical equations? Please, add a reference. If snow density was measured, it may be another useful parameter to be discussed in relation to the albedo change.”

R: References now provided: Sihvola and Tiuri (1986), and Toikka (1992). We did not use here the density information and the Materials and methods is now updated accordingly:

“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 (www.toikkaoy.com). 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.“

3. **Page 7, line 7: UVI should be written UV-Index.**

R: UV Index is now used.

4. **Page 7, line 18: Is the time step the interval between a complete spectral albedo measurement? Or the interval between switching between up and downwelling spectral irradiance? Should it be in units of seconds instead of minutes? I don’t understand the sentence on lines 18-20, as there always will be uncertainties from instable skyc onditions when measurements are not fully simultaneous.**

R: The time step is between switching the up and downwelling irradiance. The bigger the time step, the better the accuracy but the more changes in irradiances. In both cases, the irradiance measured with the Bentham setup at one wavelength is of very high accuracy. E.g., 1-minute highly accurate albedo values can be interpolated at any wavelength with a 6 minute time step. 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.

5. **Page 8, line 1: ’albedo signal was slightly higher than it had been the previous evening, possible due to frost conditions’. Figure 5 shows that the bottom surface had liquid water (24 cm), and Figure 6 showed a temperature profile close to melting conditions (0 degree), possibly water vapor from the ground enters surface layer, forming ice crust. Which could be discussed further in the Discussion part.**

   R: We thank the Referee for studying our results most carefully, and giving this comment. We have earlier suggested (Meinander et al. 2009) in a small case study, that the albedo SZA asymmetry could in some cases be due to frost on the snow surface in the morning. We then studied meteorological data in connection with albedo data. No snow liquid content data was then available. We agree to the suggestion of the Referee that, with results on temperature profile and snow liquid content, water vapour could enter from the ground and form ice crust on the snow surface layer. The ice crust could then affect the albedo by increasing albedo when icy, and decreasing albedo when melting from the surface.

In our original manuscript, we included more results on the SZA asymmetry. In the revised version, we have re-organized the manuscript and removed the SZA asymmetry equation and most of the discussion. The focus in the revised manuscript is now more on the low albedo results compared to literature of clean snow, as well as on the snow impurities. Even though, we have included in the revised version the following short new text in the Discussion on the basis of this comment by the Referee:

"Here, the bottom surface (24 cm) had liquid water, and a temperature profile close to melting conditions (0 ^oC), suggests that water vapour from the ground could possibly enter the snow surface layer, forming ice crust. The ice crust could then affect the albedo by increasing albedo when icy, and decreasing albedo when melting from the surface. "

6. page 8, equation 1. In order to be valid for forenoon and afternoon, c must be positive in the afternoon.

R: We agree. However, we suggest to remove the equation from the revised manuscript, as our focus on the revised version is on the spectral albedo values and the impurity concentrations. Therefore in the revised version Eq.1 is now removed.

7. Page 11, equation 4: The equation is basically the same as equations 1-2-3, but summarizing the c-coefficient. Please, consider if this could be simplified, by a table, or moved to page 8 where the equation first appeared.

R: We agree that Eq. 1 and 4 are basically the same and suggest to remove both these equations from the revised manuscript. We are interested in the rate of the albedo decrease and also to investigate if this rate is different for different wavelengths (Eq. 2 and 3).

Referee's Comments on Figures

Figure 2: The small dots are almost invisible. Any explanation why the albedo is not monotonically decreasing during the clear sky day, but has a hump in the middle?

R: We agree that there is a hump in the middle in the clear sky day albedo at around 6 UTC and after. The monotonical decrease is then from 9 UTC to 15 UTC. For explaining the hump on the basis of the snow conditions (Table 1) and our ancillary data, we found that the previous day (21 April 17:30 UTC) showed a separate new snow surface layer, while 22 April at 12:35 the new snow surface layer had disappeared. On 22 April, the two snow liquid water content measurement results between 6 and 9 UTC suggest an increase of water at 2 cm and 6 cm depths, while the surface (0 cm) value remains lower. Also the water content is higher at the bottom of the snow pack. After 9 UTC the water content of the 3 top surface layers started to increase. For explaining the hump on the basis of the cloudiness information, we can see from the Fig.1 of the original manuscript that the incoming irradiance suggests clear sky conditions. Hence, the hump is possibly due to the change of some property on the snow surface, related to the melt process metamorphosis, and perhaps related to the disappearance of the new snow surface layer or crust on the snow surface.

Figure 3: Due to theory of Wiscombe, Spectral albedo is expected to decrease with increasing grain size, as a function of wavelength (observations 15-17 UTC). Observations at 9-11-13, in the melting process shows the opposite. Is this due to increasing extinction in the UV from impurities in the snow, as the radiation enters deeper into the snow?

R: This we find an important point for the revised manuscript now dealing with the albedo and snow impurities. On the basis of this comment by Referee#2, we have now included the following new text in the Discussion:

"The spectral albedo results in Fig. 4 show the decrease of albedo as a function of time (the upper panel), and the relative wavelength dependent change (the lower panel). From the upper panel we can see the chronological order from highest albedo to lowest albedo (from 9 to 17 UTC). This decrease in albedo as a function of time is according to the snow grain size (Table 1), changing from 0.25 mm to 3 mm diameter grains as a function of time. These results agree with the Wiscombe and Warren (1980) paper, where albedo is expected to decrease with increasing grain size.
The lower panel shows that the spectral change (compared to the 9 UTC albedo) is first the bigger the shorter the wavelength (the 11 and 13 UTC values). This is consistent with the theoretical results of Warren and Wiscombe (1980), which show that absorption due to impurities in snow increases with decreasing wavelength. At 15 UTC this spectral behavior seems to disappear and the albedo values are 90 % of those in the morning regardless the wavelength. The SZA is then ~ 70^o. At 17 UTC, with SZA = 83^o, the spectral behavior turns slightly toward the opposite, the difference from the morning values is larger for VIS than UV. At large zenith angles, the proportion of diffuse radiation is increased as the direct part then drastically decreases (e.g. Fig. 8 of Gardner and Sharp, 2010), and the snow albedo is known to decrease as a function of wavelength as the diffuse-to- direct radiation ratio increases (Fig. 12 of Wiscombe and Warren 1980)."

8. **Figure 4: Maybe this figure is obsolete, as it represents another snow field.**

   R: We agree with the Referee that the primary albedo data is the Bentham data set and the primary field of study was the Bentham albedo field. In the revised version we focus on the primary results, but the supportive broadband data are also presented to support the low albedo values that were detected.

9. **Figure 5: Figure is easier to read if x-axis is given in hourly intervals, for comparison with Figure 2.**

R. We agree and have now prepared the figure to have the x-axis in hourly intervals.

10. **Figure 6: Consider switching x-and y-axis, so that y-axis gives the snow depth.**

    R: The figure was removed from the revised version.