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Solar Zenith Angle Asymmetry Cases in Polar Snow UV Albedo

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Abstract

We have detected an up to 10 % decrease in UV snow albedo as a function of time within a day, ranging from 0.77 to 0.67 in the Arctic, and from 0.96 to 0.86 in the Antarctic. These results are based on two separate data sets measured independently. Albedo changes are presented for five different cases (days) utilizing meteorological data on air and surface temperatures, relative humidity, and dew point temperature, in order to explain albedo changes. In all cases, the decline in albedo during the day was observed when melting occurred. Our results revealed two cases of albedo asymmetry with high relative humidity and low surface temperature during the previous night, favorable to frost and higher albedo on the next morning; one with new snow on the previous night; and two with snow melting during day time and refreezing during night. Thus, a physical explanation could be given to all the observed solar zenith angle asymmetry cases of the polar snow UV albedo. Our results may have implications for climate modeling of the changes in polar environments.

Key words: Arctic, Antarctic, snow, melting, albedo, UV

1. *Introduction*

The surface albedo, that is especially high for snow-covered surfaces, is an essential parameter for various applications based on radiative transfer modelling (e.g, *Kylling et al*., 2000), as well as for climate studies (e.g., *Pedersen and Winther,* 2005). Albedo is wavelength (λ) dependent, and has been defined (*Seckmeyer et al*., 2001):

$$a = \frac{M_G}{E_G} \quad (1)$$

where a is the reflectance of the Earth's surface, irradiated by sun and sky radiation

E_G is the short-wave global irradiance

M_G is the radiant exitance of the Earth's surface, i.e., the ratio between the radiant power Φ reflected from the surface in the wavelength range 0.3 μm – 3 μm and the area A of the surface.

Snow albedo has been studied by means of theoretical studies and modelling (e.g., *Warren and Wiscombe*, 1980; *Wiscombe and Warren*, 1980), and experiments (e.g., *Grennfell and Perovich*, 2004). Snow albedo varies according to various factors, such as snow grain size, age of snow, snow height, solar zenith angle, and soot on the snow. Albedo can be very variable and inhomogeneous around a measurement site (*Smolskaia et al*., 1999; *Weihs et al*., 2001; *Blumthaler et al*., 2009). Therefore an "effective" albedo is often defined to describe the net effect of the albedo, as derived by comparison with a model (e.g. *Schwander et al*., 1999; *Kylling et al*., 2000; *Smolskaia et al*., 2003; *Bernhard et al*., 2007).

In this study, we are focusing on the albedo at the ultraviolet (UV) wavelength range, and above all, on the albedo solar zenith angle (SZA) asymmetry. By albedo SZA asymmetry we mean, that for the same SZA, the albedo is different at different times of day, and this difference is not caused by the changes in the incoming short wave radiation (E_G) (e.g., changes in cloudiness that cause changes in E_G). Diurnal SZA symmetry, or asymmetry of snow albedo signal, may contain a temporary diurnal decrease (~1–2 hours decline after midday, and recovery thereafter), due to snow melt and increase of the effective grain size (*Meinander et al*., 2008).

The sources of uncertainty, in the determination of the SZA asymmetry, can be due to i) the improper leveling of the sensor; ii) uneven snow surface (e.g., Antarctic sastrugi); iii) shadowing due to objects (containers, houses, trees, slopes) in the vinicity of the measurement site; iv) the different cosine behavior in different azimuthal planes of the diffusers (*Meinander et al*., 2006).

Our work presented here is part of the International Polar Year IPY ORACLE-O3 cluster project (Ozone layer and UV radiation in a changing climate evaluated during IPY, http://www.awi-potsdam.de/atmo/ORACLE-O3), which deals with experimental and modelling research on the ozone layer, UV radiation and the effects of personal UV exposure during the IPY 2007-2008. During IPY, our UV related Finnish effort included the start of new continuous measurements on Arctic snow UV albedo, in Sodankylä, in 2007 (*Meinander et al*., 2008). In this work, we focus on four SZA asymmetry cases found in these Arctic data, and further compare them with one Antarctic data case of Neumayer, showing similar albedo decline within the day (*Wuttke et al*., 2006). Furthermore, we analyze these SZA asymmetric snow UV albedo cases with respect to meteorological data on air, surface, dew point temperature, and relative humidity, in order to investigate possible physical explanations linked with these findings.

2. Data

2.1 Albedo data

Snow UV albedo was measured independently with similar measurement equipment at two different locations, one in the Arctic, and one in the Antarctic. The same type of sensors, Biometer Model 501 from Solar Light Co. (SL501), were used.

The data were recorded in 1-minute intervals. The Arctic measurements were made 25.2. – 15.5.2007 at Sodankylä, (67°22'N, 26°39'E, 179 m asl), Finland. For the Arctic UV albedo measurements, two SL501 sensors with similar spectral and cosine responses were used, one facing upwards, and the other downwards, at a height of 2 m. More detailed description on materials and methods, and other parameters can be found in *Meinander et al*. (2008). The Antarctic measurements with one SL501 radiometer were performed at the German Antarctic Neumayer Station (70°39'S, 8°15'W) during 15 days between 11.12.2003 – 8.1.2004, in the austral summer of 2003/04. Albedo measurements were obtained by turning this sensor periodically upwards and downwards. More details related with the Antarctic measurements can be found in *Wuttke* (2005), and *Wuttke et al*. (2006).

The SL501 spectral response approximates the action spectrum for erythema, wavelengths in the UVB (280–310 nm) (*Seckmeyer et al*., 2005). The albedo of snow (*A*) was calculated from the ratio of upwelling UV irradiance to downwelling irradiance:

$$A = \frac{\text{UVery}\uparrow}{\text{UVery}\downarrow} \tag{2}$$

where *A* is albedo, UVery↑ is the upward erythemally weighted UV, UVery↓ is the downward erythemally weighted UV.

The Sodankylä Arctic measurements produced continuous 1-min albedo data with one sensor looking up and the other down simultaneously. The original Antarctic data were recorded in 1-minute intervals using one sensor facing up for 10 min, and then down for 10 min. In *Wuttke et al*. (2006), these measurements were used as 8-minute mean values. Here, we wanted these Antarctic data to represent data similar to our Arctic comparison data, and the momentary (instantaneous) albedo was calculated from the 1-min values closest to the turning. Therefore, we achieve a momentary albedo value with every turning up or down. Using 8 minute averages of upwelling followed by 8 minutes of downwelling, we have 1 albedo measurement every 16 minutes from the 8-min averages, and 2 albedo measurements every 16 minutes from 2 simultaneous (momentary) averages. The minute before and after turning is affected by the turning itself, so it is not used to calculate albedo (similarily these were not used to calculate the 8-min mean values either).

2.2 Meteorological data

At the Sodankylä Arctic Research Center of the Finnish Meteorological Institute (FMI), we get meteorological data on air temperature, dew point temperature, snow depth, minimum ground temperature, etc., once a minute by an automatic weather station (AWS). In wintertime, the AWS minimum ground temperature is measured between 8 pm – 8 am on the snow surface (minimum snow surface temperature). The operator puts the thermometer on the snow surface in the evening. At the Alfred Wegener Institute's (AWI) Antarctic station of Neumayer, synoptic observations are carried out every three hours. In addition, we used Neumayer surface temperature data of the www.awi.de Neumayer data base, derived from the long-wave upward radiation data of Neumayer, assuming a black-body surface.

2.3 Errors and uncertainties

The absolute values of albedo may depend on the corrections applied, yet the possible SZA asymmetry, as described here, would remain. In general, the determination of the albedo is uncertain due to imperfect cosine optics (e.g., *Bernhard and Seckmeyer*, 1999, *Cordero et al*., 2008). The effect of the cosine error becomes most pronounced when surface albedo close to unity is observed (*Wuttke et al*., 2006). For the particular study, the measured angular responses of the two Arctic SL-501 biometers were used to quantify uncertainties due to cosine error. Integrating incoming radiances over the whole hemisphere, and assuming isotropic distribution of the diffuse scattered light, we calculated an error of the incoming scattered light contribution of 0.5 % and 3.2 % for the up-welling and down-welling sensor, respectively. Based on the cosine correction theory described in *Seckmeyer et al*. (2005), we used radiative transfer modeling calculations for the SZA measurements range (55–80 degrees). For cloudy conditions (no direct sunlight contribution to the total irradiance measured), this difference in the angular response could lead to a systematic but small (2.7 %) overestimation of the measured UV albedo, independent of SZA changes. For cloudless conditions (direct sunlight contribution), this overestimation ranges from 0 % to 3.5 % for SZA's of 55 and 80 degrees, respectively.

Earlier, the effect of the cosine error of the Antarctic biometer SL501 has been discussed in *Wuttke et al*. (2006). It was found that for these Antarctic data, the SL501 underestimated the downwelling irradiance compared to the spectroradiometer by 1–15 %, depending on SZA, and the cloud situation. The largest deviations between the SL501 and the spectroradiometer occurred at the largest SZA (59.5–62 degrees), indicating a cosine error. However, the cosine error was not clearer in the cloudless data, and there was no indication that the instrument would not have an angular response differing much from the angular response typical for such instruments (*Seckmeyer et al*., 2005). The angular response has not been measured for this specific SL501, but the data used here were corrected for the change in SZA during the 8-min intervals of up- and downwelling measurements.

Additionally, instrumental factors of leveling, shadows, etc., can possibly introduce small errors. In our cases leveling was made carefully, and the measurement place was selected with minimum shadowing effects (*Wuttke et al*., 2006, *Meinander et al*., 2008). In the Arctic data, two sensors were measuring simultaneously. These sensors were with similar spectral responses, thus resulting in errors of less than 1% due to such differences (*WMO,* 1996). In the Antarctic data, the turning of the sensor periodically was approximated to produce a leveling uncertainty of ±0.02 (*Wuttke et al*., 2006).

Considerable efforts to analyse the uncertainty of the spectroradiometric measurements have been made in the past (e.g., *Bernhard and Seckmeyer*, 1999), and recently (e.g., *Cordero et al.*, 2008.). Such comprehensive uncertainty analysis are too complex and lengthy to be discussed in detail here. From these analysis it is concluded, that the uncertainty of measuring the absolute irradiance is at least as much as 6 % for erythemal weighted irradiance, and at least 10 % for wavelengths below 300 nm. However, most of these uncertainties are much reduced because the measurement of albedo is a relative measurement from the radiometric viewpoint. Especially the asymmetry of the albedo can be assessed with an estimated uncertainty of about 2 % or less.

3. Results

3.1 Arctic albedo

At Sodankylä, in April 2007, with the midday SZA angle between 53–63 degrees, four days indicating SZA asymmetry in the measured data have been found (12, 14, 24, and 27 April). During the asymmetry days, the cloud cover was variable, snow melting occurred, and the midday SZA was from 53.8 to 59.0 degrees. The incoming irradiance is available from the upward looking sensor, and this information can be used to study possible effects of changes in cloudiness (Fig. 1). The Arctic albedo decline ranged approximately from 0.77 to 0.66 (12 April); 0.66–0.6 (14 April), 0.58–0.52 (24 April), and 0.49–0.46 (27 April), when a temporal (~1-2 hours) diurnal decline after midday, and recovery thereafter, is not taken into account (Fig. 1). Hence, the albedo decline within a day was up to 10 %, with the mean value of 0.07, in these Arctic data.

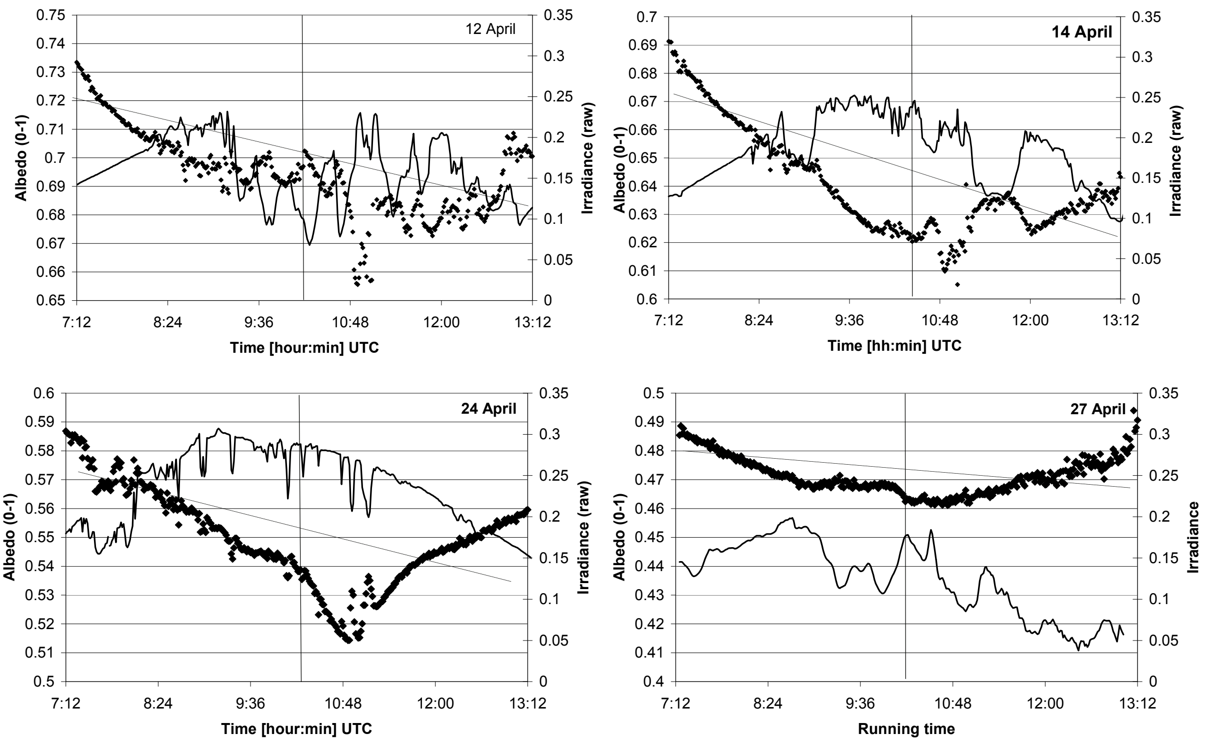

Fig. 1. The four cases of SZA asymmetry (12, 14, 24, 27 April 2007) in the Arctic snow UV albedo at Sodankylä. The incoming irradiance (line) indicates changes in cloudiness. The measured UV albedo (filled squares) shows SZA asymmetry. The solar midday is indicated with a vertical line, a descending line is drawn to demonstrate the albedo decline, and the y-axis is scaled to show a difference of 0.1 in albedo.

3.2 *Arctic meteorological data*

In April, there was snow on the ground during the whole month (Fig. 2). The snow depth decreased monotonically after 12 April, until totally melted. The dew point (frost point) temperature was often 5–15 °C colder than the air temperature, but on 11 and 27 April dew point and air temperature were very close to each other (Fig. 3). The days with relative humidity (RH) greater than 80 % were: 1, 4, 11, 16, 21, 23, 25, 27, and 29 April.

With respect to the SZA asymmetry cases (12, 14, 24, and 27 April), the summary on the meteorological observations is as follows:

- r*elative humidity:* days 11 and 23 April, prior to the asymmetry cases, indicated high RH. On 11 April, RH was from 84 % (morning) to 97 % (evening). On 23 April, RH increased from 63 % (morning) to 97 % (evening)
- *dew point* (frost point) was below freezing on 11–12, 13–14, partly 23, whole 24, and in the morning of 27 April
- *snow height*: from 10 to 11 April, the height of the snowpack increased by 2 cm, and from 11 to 12 April by 4 cm. From 12 to 13 April, snow height decreased by 2 cm. Hence, on the asymmetry case of 12 April, there was new snow on the

previous day, and metamorphosis and/or melt of snow during the day of asymmetry.

– *minimum temperature of the snow surface:* every night before the SZA asymmetry days, the snow surface was always frozen in the evening, night and early morning hours (Fig. 4). During the following SZA asymmetry day, the air temperature at 2 m heigth (T2) reached 5.5 ^{o}C (12.4.), 9.6 ^{o}C (14.4.), 5.7 ^{o}C (24.4.), 7.5 ^{o}C (27.4.), and the snow was melting, and there was snow on the ground (Fig. 2).

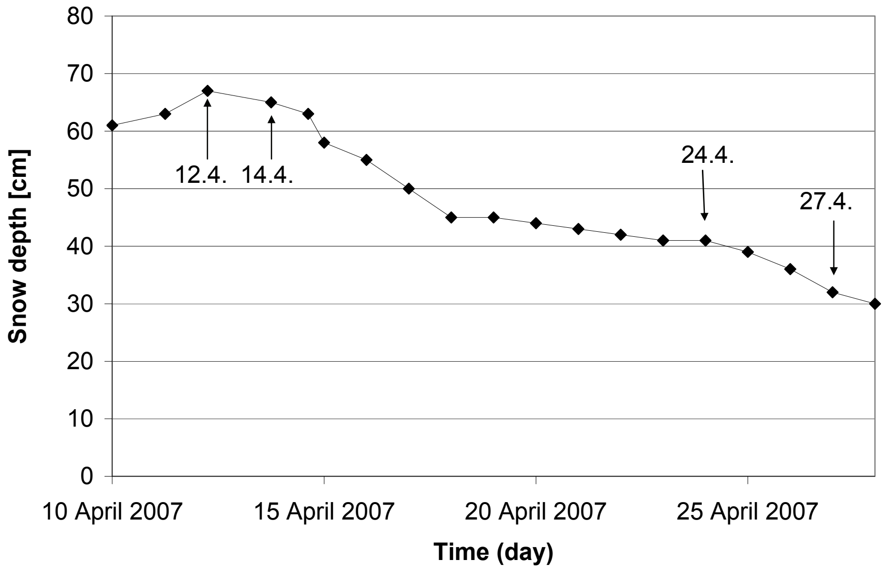

Fig. 2. Snow depth in Sodankylä in April 2007.

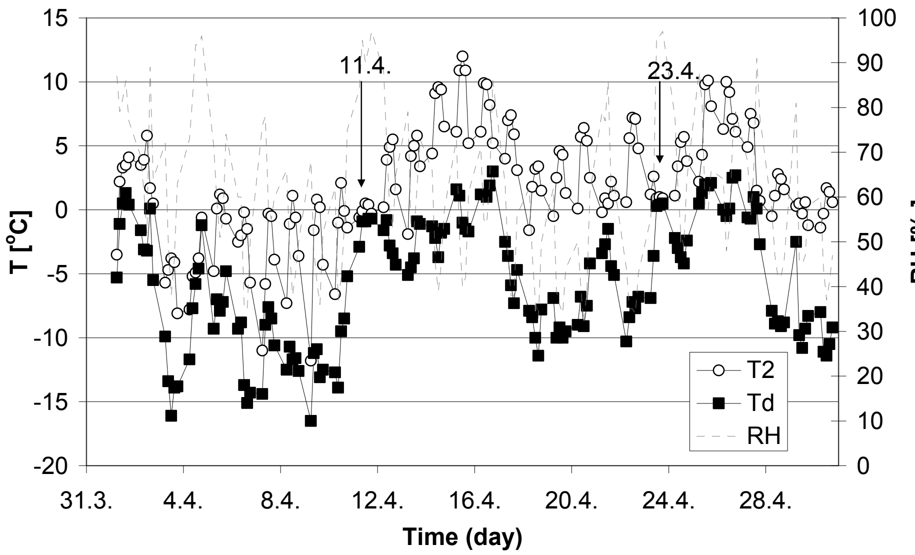

Fig. 3. Air temperature T2 (open circles), dew point temperature Td (filled squares), and relative humidity RH (line), Sodankylä, 1–30 April 2007, based on SYNOP observations at 6, 9, 12, 15, and 18 UTC each day.

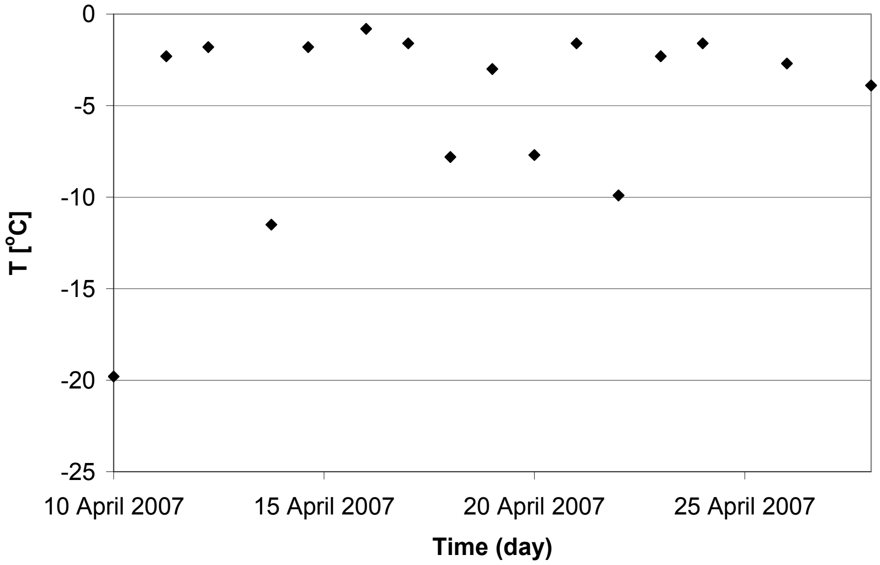

Fig. 4. The minimum snow surface temperature T_{min} at Sodankylä, April 2007.

3.3 *Antarctic albedo*

The Antarctic snow UV albedo decline case occurred on 4 January 2004 (Fig. 5), and could be observed by spectral measurements as well (*Wuttke et al.*, 2006). The solar noon was then at 12.30 UTC with the SZA of 47.59 degrees. Our assumption was, that the difference between 8-min and 1-min results should be insignificant, and the results were as follows: a) Using the new re-calculated 1-min data for 4 January 2004, we calculated the simple SZA dependent empirical albedo decline, using a simple linear regression approach (albedo = f * SZA). This slope f was calculated to equal with -0.0024; b) Using the original 8 minute-average-data, the decline during the day new slopes (f) were -0.002 for the afternoon data only, and -0.0028 for the whole day. In general, the Antarctic albedo was ranging from ~ 0.96–0.98 (0.98 in 1-min data, and 0.96 using 8-min data) to 0.86, resulting in a decline of ~0.10–0.12 (~10 %) towards the afternoon.

3.4 *Antarctic meteorological data*

In the Antarctic case, a frozen snow surface in the morning was observed, and the later the day (especially with days with no or little clouds), the slushier the snow surface. On 3 January, the daily maximum air temperature record was -0.3 ^{o}C, and on 4 January it was 0.4 ^{o}C. On 4 January, the sky was relatively clear during the afternoon hours (Fig. 6). On 3 January, the wind speed was quite significant, ~ 10 m/s between 6 UTC and the next morning. During 4 January it calmed down to ~ 3 m/s (very week wind) on the afternoon (Table 1). The dew point temperature was colder than the air temperature, but they were not close to each other. The derived surface temperature, according to the Alfred-Wegener-Institut's (AWI) Neumayer data base, was above zero on both days (Fig. 7): on 3 January from 10:40 to 16 UTC, and on 4 January from 12 to 3:40 UTC.

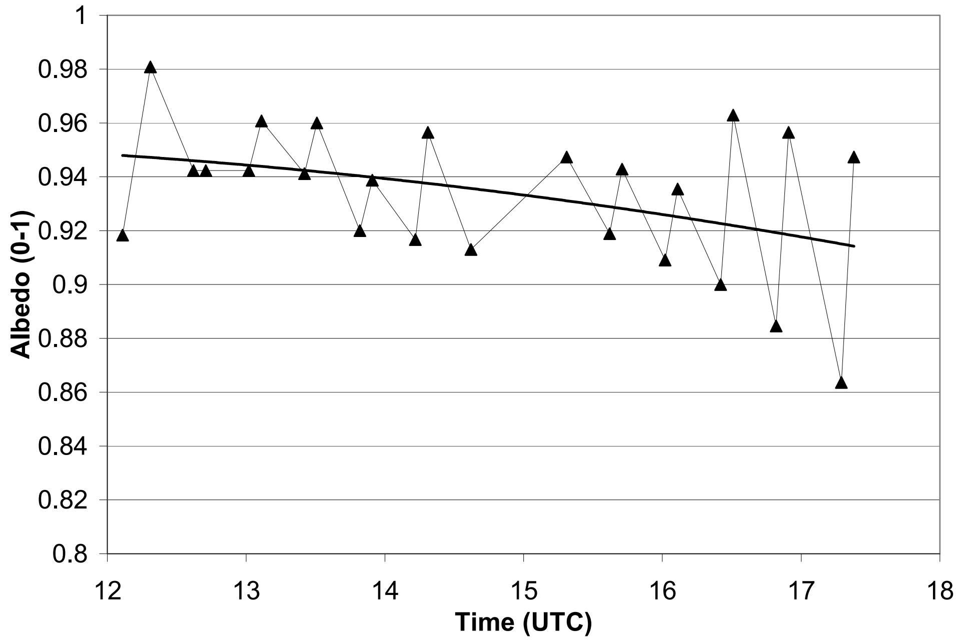

Fig. 5. The re-calculated 1-min albedo data of the Antarctic SZA asymmetry case on 4 January 2004 at Neumayer, with a linear fit calculated by the least squares method.

Table 1. The results on the weather parameters at Neumayer, Antarctic, 3 and 4 January 2004.

Time	**Td [^{o}C]**	**T [^{o}C]**	**Wind Speed [m/s]**	**Total cloudiness**
Jan 3 2004 12:00AM	-3.8	-2.4	4.63	7/8
Jan 3 2004 3:00AM	-3.1	-2.0	6.17	8/8
Jan 3 2004 6:00AM	-2.0	-0.7	11.32	8/8
Jan 3 2004 9:00AM	-3.5	-0.8	13.37	8/8
Jan 3 2004 12:00PM	-1.9	-0.7	10.80	8/8
Jan 3 2004 3:00PM	-1.3	0.1	10.80	7/8
Jan 3 2004 6:00PM	-1.4	-0.4	12.35	-
Jan 3 2004 9:00PM	-1.8	-0.7	9.77	-
Jan 4 2004 12:00AM	-2.4	-0.9	10.80	7/8
Jan 4 2004 3:00AM	-3.9	-1.3	10.80	-
Jan 4 2004 6:00AM	-4.1	-1.5	9.26	7/8
Jan 4 2004 9:00 AM	-3.7	-1.4	8.74	8/8
Jan 4 2004 12:00PM	-3.5	-0.7	6.17	7/8
Jan 4 2004 3:00PM	-3.4	-0.1	3.60	2/8
Jan 4 2004 6:00PM	-3.1	-1.0	2.57	2/8
Jan 4 2004 9:00PM	-3.9	-2.6	4.12	4/8

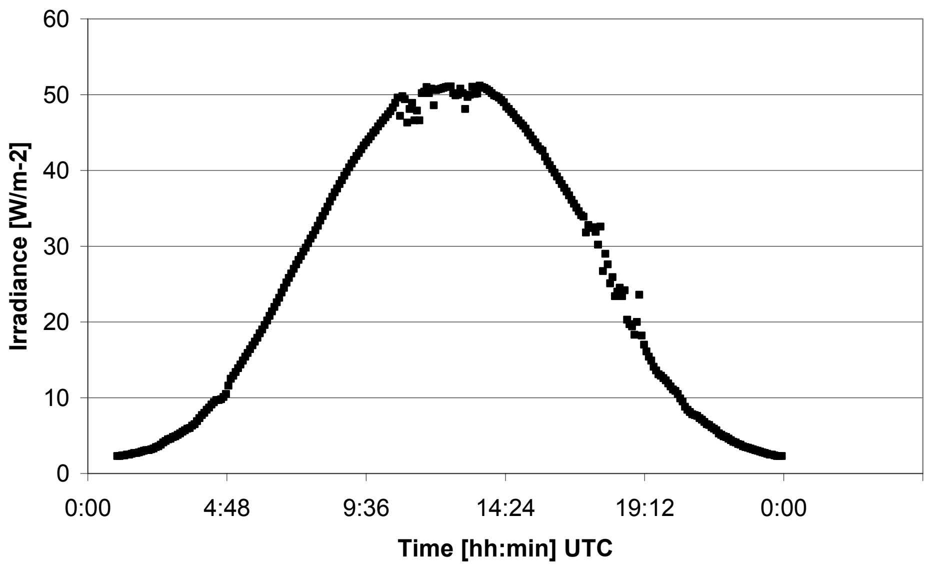

Fig. 6. Antarctic UV irradiance at 300–370 nm [W/m2] for the day 4 January 2004 at 5-min time resolution (running time), according to the AWI data base of Neumayer, showing relatively clear sky conditions during the day.

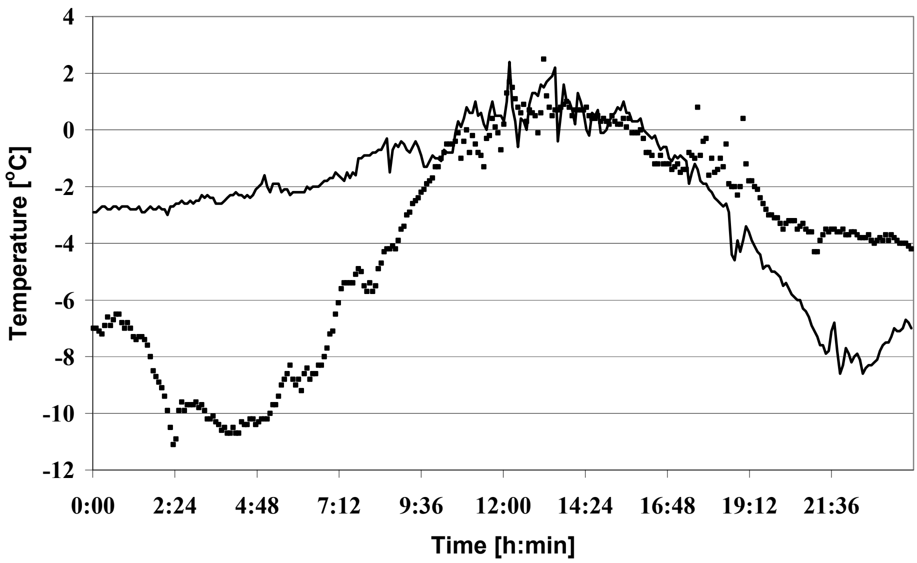

Fig. 7. The derived 5-minute means of surface temperature on 3 January (line) and 4 January (points) 2004, at Neumayer, Antarctica.

4. *Discussion and conclusions*

Here our focus was on the SZA asymmetry cases in snow UV albedo, and the physical explanations behind the observations. We found cases where snow UV albedo was different for the same solar zenith angles at different times of day. An up to 10 % decrease in albedo was found as a function of time within a day, ranging from 0.77 to 0.67 in the Arctic, and from 0.96 to 0.86 in the Antarctic. In all these five study cases, the decline in albedo during the day was observed, when melting occurred.

In the Arctic data of Sodankylä, the asymmetry cases were found on the 12, 14, 24, and 27 April. Every night before the SZA asymmetry days, the snow surface was always frozen in the evening, night and early morning hours (Fig. 4). The next day, T2 reached temperatures from 5.5 to 9.6 ^{o}C. Although snow melt, there was snow on the ground (Fig. 2). In addition, all data after 12 April represent the snow melt period. For the first asymmetry case of 12 April, new snow accumulated on the previous day (Fig. 8) is the most probable reason for the higher albedo (~0.75) during morning hours. The metamorphosis and/or melt of snow during the next day (12 April) could result in an albedo decrease. In addition, as the air temperature was very close to the dew point temperature then (Fig. 3), we can assume that frost has occurred on 11 and on 23 April, as frost on snow surface depends on surface temperature. The asymmetry observed on 12 and 24 April, is therefore most probably due to frost formed on the ground during the previous evening and night hours, resulting higher albedo measured during the following morning. The albedo then slightly decreases during the day, as the frost disappears. On 27 April, the decline in albedo within the day would result from snow melt during day, and refreezing of snow in the evening, night and early morning hours. We can conclude that in all other asymmetry cases, except the new snow case of 12 April, the melting during day and re-freezing during night might be the main reason for the diurnal albedo asymmetry findings.

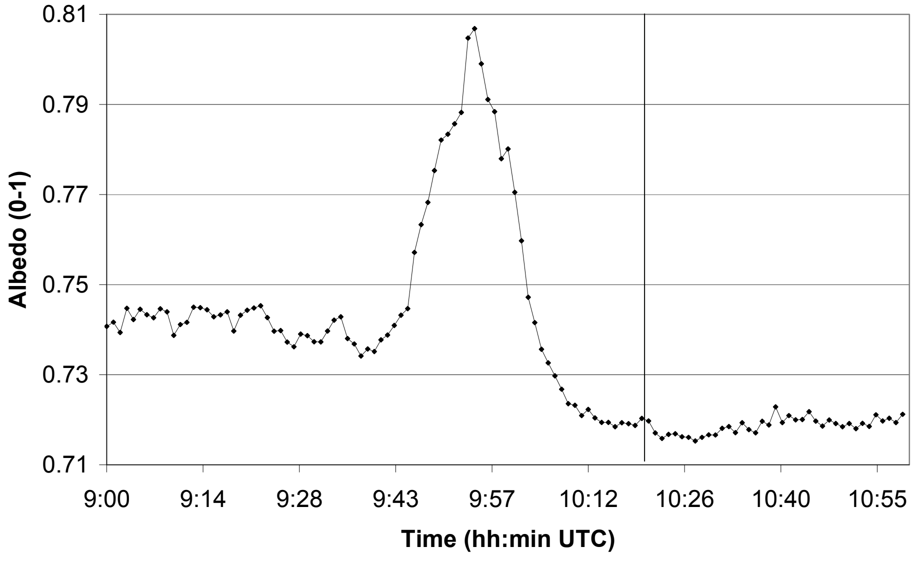

Fig. 8. The albedo of Arctic snow on 11 April, i.e., the day prior to the albedo asymmetry case of 12 April. Before midday (marked with a vertical line), the temporary increase in albedo is most probably due to new snow that increased by 8 cm during the day. The afternoon albedo value was ~ 0.72.

In the Antarctic data of Neumayer, the asymmetry was found on 4 January 2004. This decline of albedo for increasing SZA had, in fact, been observed with three different instruments independently (*Wuttke et al*., 2006). In the study at Neumayer by *Wuttke et al*. (2006), the meteorological parameters have not been used to study the SZA asymmetry in more detail. Here, we found that the calculated temperature at the snow surface, extracted from www.awi.de Neumayer data base, indicated temperatures above zero during afternoon on the day of asymmetry, and the previous day. During evening and night, the temperatures were below freezing. Visual observations at the site confirm these results, i.e. the snow surface was frozen each morning, and the later the day, especially with days with no or little clouds, the slushier the snow surface. Frost point temperature and air temperature were not close to each other, and frost is not assumed. Therefore, metamorphosis and re-freezing is probable to have taken place. On 3 January (prior to the asymmetry day), the wind of ~10 m/s is probably linked with mechanical production of smaller snow grain sizes, resulting higher albedo for the next morning. During the calm day (4 January) with warming solar irradiance these grains would then go through metamorphosis, showing a decreasing albedo as function of time.

In our measurement data, there were originally two snow surface temperature measurement results above 0 ^{o}C (data corrected in Fig. 4). It is difficult to avoid measurement errors in the snow surface temperature, especially during daylight, due to the absorption of solar radiation by the thermistors. Errors may be even as large as some degree Celsius. The rule generally used to correct the snow temperature measurements (derived from thermistor or from pyrgeometers) is that when air temperature is above zero, the maximum allowed snow surface temperature is zero. In our case of minimum temperature between 8 pm – 8 am, it is unprobable that the results would suffer from solar radiation effects. Basically, the error might be due to a calibration problem, or the fact that the measurement is not representative as a snow surface temperature measurement, but rather a measurement of the temperature of the snow-air-water mixture. In addition, before any meltwater can leave the snowpack, the liquid water holding capacity of snow must be surpassed, and the capacities can vary greatly (e.g., *Kuusisto*, 1984). On the other hand, *Gold and Williams* (1960) have stated, that if the snow cover is actively melting, the assumption that the surface is at 0 ^{o}C can not be stricly valid, as the heat required to melt the ice must pass through a film of water on the ice surface, and therefore the air-water interface must be somewhat above 0 ^{o}C. More recently, *Makkonen* (1997), has presented a new theory on surface melting of ice, also explaining why water reaches a density maximum above its freezing point. According to that theory, the theoretical melting temperature of bulk ice would be approximately + 8 ^{o}C. Hence, further analysis on wellcalibrated and documented measurements on the surface temperature of melting snow may be needed. It should be emphasized that the physical processes at the snow surface may be rather complex, due to phase transition processes between solid, liquid, and gas phase of ice and water vapor.

On the basis of our results, a physical explanation for the observed albedo asymmetry can be hypothesized. Our null-hypothesis is: UV albedo is symmetrical to SZA. Then, our working hypothesis is: snow UV albedo may have SZA asymmetry that has a physical explanation. The physical reasons behind SZA asymmetry could be: i) snow melting and refreezing, ii) new snow, iii) frost, or iv) ice crystals directly depositing on the surfaces. Evidence to cases i-iii were presented in this work. Summarizing the above results, the following processes could be responsible for the observed SZA asymmetry:

1. Snow surface is below freezing during night. Moisture in the air makes frost on the snow surface during evening and night, and higher albedo is observed in the following morning. The effect of frost disappears towards afternoon as the frost melts (or evaporates) from the surface. The physical process on the surface may be quite complex, as we are dealing with a transition between solid and gas state here. But, as a result, the albedo declines within the day.
2. In case of no frost, the melting of the snow surface during day leads to a decrease in the albedo, as the effective grain size increases. Re-freezing during night contributes to the higher albedo of snow in the morning, as the effective grain sizes decreases again.
3. New snow during the previous evening and night, or in the morning of the albedo asymmetry day, can result in a higher albedo for the morning hours. This albedo may decrease as a function of time due to changes of the snow properties.

In order to systematically detect and better understand asymmetry cases in snow albedo data more spatial, temporal and wavelength dependent information are needed. When analyzing long-term 1-min data sets of albedo and meteorological data, we might benefit from rules or criteria to detect and analyze albedo decline, and its possible causes with automatic routines. Automatic detection could be of use to develop model parameterizations for wavelength dependent (here UV) and diurnal albedo changes. For the SZA asymmetry detection, a certain limit in the albedo decline would then be set on the basis of larger materials, and considering that the asymmetry of the albedo can be assessed with an estimated uncertainty of about 2 % or less. After detecting the possible decline cases, simple meteorological parameter criteria would be needed. E.g., we can assume frost possible, if the temperature of the surface is below freezing, or if the air temperature is close to the dew point temperature, combined with high relative humidity. In turn, melting and refreezing can be considered possible, if the surface/air temperature is non-negative during day, and below zero during night.

In *Grenfell et al*. (1994), and in *Wiscombe and Warren* (1980), an increase in albedo for increasing SZA has been observed. Here, we found albedo to decrease with increasing SZA. In reality, the decrease in albedo during the day is simply due to the pronounced snow metamorphism that takes place during melting conditions, therefore the observed diurnal variation is expected. These observations do not contradict the theory of albedo dependence on solar zenith angle (according to which the albedo decreases with decreasing SZA, e.g., *Grenfell et al*., 1994; *Li and Zhou*, 2003), but they simply show that during the melting conditions the effect of metamorphism dominates over the solar zenith angle.

The same decrease feature has also been observed by *Pirazzini* (2004) in the Antarctic at three locations, and *Pirazzini et al*. (2006) in the Arctic snow and ice albedo data. *Pirazzini* (2004) suggested for Antarctic snow: $A = A_{\mathrm{midday}} + c(\mathrm{SZA}-\mathrm{SZA}_{\mathrm{min}})$, where c = -0.003 was the best value for c in the afternoon. Their measurements were made with pyranometers (broadband signal for ~300 nm – 3000 nm). Here, we found an

UV albedo decline *A* = -0.0024*SZA. The differences between the results by Pirazzini and our study show very little significance. The results were obtained over the same Antarctic location of Neumeyer, same season, and similar weather conditions. Only the wavelength range is different. According to *Grenfell et al*. (1994), the albedo has a uniformly high value of 0.96–0.98 across the UV and visible spectrum, nearly independent of snow grain size and solar zenith angle, and this value probably applies throughout the interior of Antarctica. They state the albedo in the near IR to be lower, dropping below 0.15 in the strong absorption bands at 1.5 and 2.0 μm, and to be quite sensitive to grain size and somewhat sensitive to zenith angle. *Perovich et al*. (1998) examined UV and visible albedo and found the albedo to decrease at all wavelenghts during melt. The decrease was greater at UV than at blue-green. According to *Wiscombe & Warren* (1980), the visible albedo for pure snow appears rather insensitive, and near-IR albedo very sensitive to snow grain size. The impurities in the snow have been found to depress albedo at visible wavelengths, but have little effect in the infrared (*Grenfell et al*., 1981, *Warren & Wiscombe*, 1980).

If not already installed, climate modelers should take into account both the diurnal and the wavelength dependent variability of snow albedo in their parametrizations. Further studies need to be performed to investigate whether such dependencies will influence conclusions about the climate-albedo feedback. Albedo feedbacks are known to be important for simulating the future climate. Thus we think our findings can be useful in providing a reference for parametrization development and satellite data validation. In climate modeling, compared to a case with the same time-average snow albedo, diurnal variations in albedo might affect the diurnal mean absorbed solar radiation, making snow melt either faster or slower than in reality.

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