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Effective surface albedo due to snow cover of the surrounding area

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ABSTRACT

Albedo inversion techniques are investigated in this work. Several methods are applied to spectral irradiance data from a measurement campaign held in the German Alps during the spring of 1999. One first method is based on the comparison of measurements of absolute levels of UV irradiance with model calculations. The second method takes advantage of changes in the spectral slope of spectral UV irradiance, which is a function of the surface albedo. In the third method, the surrounding area is partitioned into snow-covered and snow-free regions, and the effective albedo estimated by applying a higher or lower reflectivity to each facet before integrating over the surroundings. We present sensitivity analysis, the differences and the correlations between the various methods as well as the results for the different locations.

Keywords: UV radiation, albedo, mountains

1. INTRODUCTION

The solar irradiance at ground level is composed of two components: The direct (unscattered) solar irradiance and the diffuse (scattered) solar irradiance. While the direct solar irradiance is only affected by the composition of the atmosphere it traverses, the diffuse irradiance is influenced by several additional parameters, one of which is the surface reflectivity (also known as surface albedo). Surface albedo is defined as the ratio of the upwelling (reflected) irradiance to the downwelling (incoming) irradiance and depends on the ground type and wavelength. While the surface reflectivity of clear water and most soils is less than 10% in the ultraviolet wavelength range, fresh snow enhances the local reflectivity to about 0.8 to 0.9 (Blumthaler (1988), Feister and Grewe (1995)).
As the terrestrial atmosphere is relatively transparent at visible and ultraviolet wavelengths, the solar radiation at a specific location on the ground is not only affected by the local surface albedo but is influenced by the characteristics of the surface albedo of an area of considerable size. Richiazzi and Gautier(1998) as well as Deguenther et al.(1998). calculated the relative enhancement of UV irradiance due to partial snow coverage and obtained estimates for the size of the area which influences the surface UV irradiance. The results of both studies indicated that the surface albedo must be known in a large area: According to Deguenther et al. even if the surface albedo is specified in an area of radius 40 km around the measuring site, the influence of areas outside this area on the UV irradiance can still be as high as 3%. It should be noted however that these model calculations disagree with the 'radius of importance' measured by Smolskaia et al.(1999) in the Antarctic which they put at around 2.5 km.
Since most radiative transfer calculations used to model UV radiation are obtained with one dimensional models (i.e. the variable parameter is the height above ground), some sort of average albedo has to be used to characterize the surface reflectivity, commonly called effective albedo.

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One possibility to obtain the effective albedo is to use the average albedo A_a of an area defined by the following equation,

$$A_a = \Sigma \; A_x S_x / 100 \qquad (1)$$

where A_x is the albedo of the surface x and S_x the percentage of the total area covered with surface type x. However it is well known that the average albedo is not only affected by the surface reflectivity of each ground type but also by the orientation of the surface terrain (Richter, 1998) relative to the incoming radiation and relative to the surrounding terrain. Thus, the task of defining the effective albedo representative for a given surface topology is a very difficult one.
One possibility to determine the average albedo of a given terrain might be to use the spatially averaged reflectivity measured by satellites which have typically a resolution of 50 to 500 km (e.g. 50 x 50 km for a view from nadir for TOMS). Eck et al. (1987) determined the average albedo using TOMS minimum reflectivity values at 370 nm over a three-month period so as to select conditions where reflectivity enhancement due to aerosols and clouds was excluded. The albedo values found by Eck et al. for the alpine regions were around 2%, but the authors mentioned problems with the altitude correction algorithm over mountainous regions that might have introduced a ±3% inaccuracy. Their values refer to an average, however, with insufficient account being taken of seasonal changes. Herman and Celarier (1997) used a longer period of 14.5 years of TOMS measurements to deduce seasonal changes in UV albedo. Their measured surface reflectivity values for the alpine regions ranged between 4 and 8% in the summer months and over 16% in winter. However, this study focused on snow-free conditions and no statement as to the exact reflection values of the alpine region was made.
Common to these studies is the relatively large ground pixel size which might not be representative for the effective albedo used in radiative transfer models.
A second approach to determine the effective albedo of a given site is to use solar radiation measurements obtained at that site combined with radiative transfer calculations. It is obtained by varying the effective albedo used in the radiative transfer calculations until best agreement with the measurements is obtained. It is obvious that additional parameters are required to constrain the model calculations, for example total column ozone and total aerosol optical depth to name the most important. Using this approach, Weihs et. al.(1999) investigated the influence of the average albedo on ground UV irradiance at Sonnblick Observatory (3106 m altitude). They found UV values in winter on average 4.5% higher than in the summer at a fixed solar zenith angle. This was most probably due to changes in surface albedo because larger areas were covered with snow during the winter. Simulations with the radiative transfer model suggested that the average albedo might be higher by 0.15 to 0.22 during wintertime as compared with summertime. However, the winter albedo values were much lower than those of a corresponding flat surface. The average albedo obtained by Pachard et al.,(1999) for the surroundings of Briancon in the French Alps was around 0.3 to 0.4 for Winter. Smolskaia et al.(1999) measured in Antarctica in cloudless conditions changes of 10 % between UV irradiance over water and UV irradiance over snow covered ice; however, McKenzie et al.(1997) measured short time enhancements in UV irradiance in partly cloudy conditions at Lauder (New Zealand) due to snow cover of up to 70%.
Kylling et al.(2000) derived the effective albedo for the region of Tromso, Norway, by using ground-based global and direct UV irradiance measurements. The derived albedo reached maximum values of 0.57 at 320 and 0.78 at 450 nm in winter. These relatively low values were attributed to the open waters surrounding Tromso all year round.
Blumthaler and Haferl (1999) determined an effective albedo at the High mountain Observatory Jungfraujoch in Switzerland of 0.45 in late spring and 0.7 to 0.8 in Winter because of changes in the snow cover. These values were determined by using a method based on the spectral shape of spectral UV irradiance scans. Schwander et al. (2000) Determined the effective albedo for Garmisch Partenkirchen, Germany, by using measured and modelled UV irradiances. They obtained regional albedo values between 0.18 and 0.5.
Schmucki et al. (2001) determined the effective albedo of the surroundings of Weissfluhjoch by using two different methods. A method which takes into account the area of the surrounding which is covered with snow. The second method used the ratio of the incident diffuse to incident direct UV irradiance. They calculated the yearly course of the average effective albedo and found values between 0.03 in Summer and 0.7 in Winter.
In this paper, we examine values of the effective albedo obtained with three different methods. Using two methods (method 1 and 2) which are based on measurements, we verify a third (method 3) that does not depend on measurements and can be applied independently. The first method makes use of the definition for effective albedo given above. The second method goes some way to removing the influence of absolute errors and other effects not connected with surface albedo by examining features of the spectrum that are a function primarily of the surface albedo. The third method can be used independently of measurements of the UV irradiance. The methods are applied to measurements

made at 6 stations situated in the southern German and northern Austrian Alps, all lying within a circle of radius 100 km. As well as results for the albedo at the different sites, some statement on the quality of the various methods can be made.

2. METHOD OF INVESTIGATION

Within the scope of the EU project CUVRA (Characterization of the UV radiation field in the Alps) a measurement campaign was organized in Garmisch Partenkirchen, Germany and surroundings in spring of 1999. The measurements included spectral UV irradiance measurements in the range 290 to 400nm, a variety of broadband and filter instruments and additional measurements of aerosol optical depth, ozone and of some snow characteristics. The aim of the campaign was the investigation of the clear sky ground UV irradiance and of its variability. Special emphasis was put on the effect of ground albedo on UV changes and therefore the measurement locations were chosen so as to maximize potential differences in surface albedo between the different measurement sites. Thus, there were two mountain sites, Wank at 1750 meter above sea level (m.a.s.l.) and Zugspitze at 2967 m.a.s.l., two valley stations, Seefeld at 1200 m.s.a.l. and Garmisch-Partenkirchen at the Fraunhofer Institut fuer atmosphaerische Umweltforschung (IFU) at 730 m.s.a.l. and finally two stations located in the plains outside of the mountaineous region at Murnauer Moos (700 m.s.a.l) and Oberpfaffenhofen (600 m.s.a.l). All stations were within an area of radius 30 km centered at Garmisch-Partenkirchen, while the site at Oberpfaffenhofen was 75 km away to the north. The measurement period of early spring was chosen because while most low lying sites were snow free, the higher lying sites of Seefeld, Wank and Zugspitze were still covered with snow. During the measurement period two days (18. and 24. March) were cloudless during the whole day and were chosen to retrieve the effective albedo at the various measurement sites.
A detailed description of the campaign and the measurements obtained at the various sites are to be found in Gröbner et al (2000) and will not be repeated here.

2.1 Snow samples

Snow samples were collected at Garmisch-Partenkirchen, Zugspitze, Wank and Seefeld during the campaign. The type and size of the grains was established from examinations of microphotographs and the soot content was determined in the laboratory. From this information the reflectivity could be calculated using the code of Wiscombe and Warren (Wiscombe and Warren, 1980). These data showed an increase in the reflectivity of the snow grains with height due to smaller grain size and less soot content at higher altitudes. The average reflectivity (from 300 to 400 nm) was between 0.78, for snow taken from below 1000 m, and 0.946, for snow found at altitudes greater than 2500 m. Additionally, the snow line was observed throughout the campaign. The snow line was at around 800 m at the start of the campaign, rising to about 1100 (± 150m depending whether it is a south or north facing slope) by the finish.

2.2. Models and inversion methods

This study compares the effective albedo obtained using three different methods. In the first method (Method 1), the effective albedo is calculated simply by comparing the absolute UV levels of the measurements with the results of calculations made using a 1-D radiative transfer model (SDISORT; Stamnes et al., 1988). The effective albedo is that albedo for which the best agreement between measurements and model is obtained. The best agreement is obtained when the average of all the ratios between 325 and 400 nm is closest to unity. More information about the input parameters to the model used for method 1 and 2 may be found in Gröbner et al. (2000). According to Gröbner et al. (2000) an uncertainty in the irradiance of ± 5% at 400 nm translates to an uncertainty of approximately ± 0.2 in the effective albedo.
The second (Method 2) is based on the relative changes in the spectral slope of the ratio of measurements to model calculations as a function of surface albedo (see also Gröbner et al., 2000). With increasing surface albedo, the UV irradiance increases proportionally more at shorter wavelengths than at wavelengths closer to the visible region of the spectrum. The effective albedo in this case is the value of the albedo used as input to the model for which the ratio of measurements to model calculations is constant (that is, flat) over the wavelength range 325 to 400 nm. According to our simulations, if the spectral slope of a scan is miscalculated by ± 1% (the 320 to 375 nm ratio is off by ± 1%), which is a rather realistic value, an error interval in the inverted albedo of the order of ± 0.082 would arise (fig. 1). An error in Angström alpha parameter of 1.6 would produce an error in inverted albedo of up to 0.2. In general errors become larger with increasing aerosol optical depth.

The third method determines the effective albedo A_a by integrating over the surrounding area of 40 km and using snow line information together with a digital elevation map (including information about the ground type of each pixel) to retrieve the effective albedo characteristic for that area.
This method is based on the following equation:

$$A_a = \sum_{i=1}^{m} A_i \, F(R) \qquad (2)$$

where A_i is the reflectivity of the pixel i and $F(R)$ is a weighting function that is a function of distance from the central pixel. The method of Lenoble (2000) was used to calculate this weighting function for the irradiance. Within the UV-A

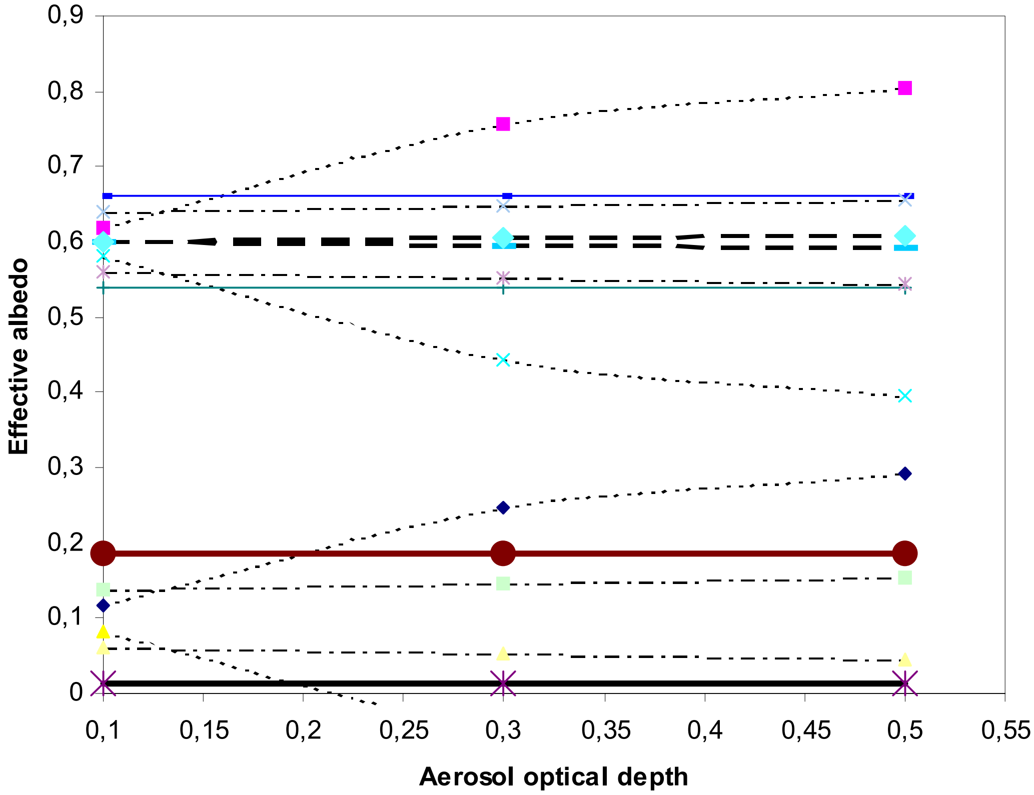

Figure 1: Analysis of possible error of the inverted albedo using method 2. The maximum and minimum values of the inverted albedo are shown for a real effective albedo of 0.1 and of 0.6. Solid lines: maximum and minimum values due to uncertainty in the spectral shape of the scan (assumption = ±1% due to cosine error, measurement unstability or calibration error). Dotted lines maximum and minimum values arising from an error in Angström alpha parameter of ± 1.6.Dashed line error due to an uncertainty in single scattering albedo of ±0.5. Dashed dotted line: uncertainty due to error in aerosol optical depth of ± 50%

wavelength range (345 to 400 nm), the function does not change significantly but at shorter wavelengths, the area which contributes to the irradiance amplification becomes less extended. This is due to a decrease of atmospheric backscattering in the region of ozone absorption, and may depend on the tropospheric ozone profile. In our calculations the contribution function for 345 nm was taken as representative for the wavelength range 325 nm to 400 nm (used for methods 1 and 2). Each pixel is defined to be either snow-covered or snow free. The value A_i for the reflectivity of a pixel is set to 0.035, if snow free, or taken to be a pre-defined function of height, if snow-covered (see section 2.1). The area of the surroundings covered with snow was estimated by combining information about the snow line with a digital elevation map of the surroundings. The snow line concept is a relatively coarse approximation. Large differences in the height of the snow line are seen between north- and south-facing slopes (see section 2.1). According to our simulations, the atmosphere (400 m thick layer) below the summit may enhance the albedo due to back scattering by 0.1 at 310 nm, and less than 0.1 in the UVA wavelength range. This is not, however, the only physical process that should be taken into account to obtain a physically accurate model. As the reflected radiance of each surrounding facet depends not only on the reflectivity but also on the illumination of the facet, the inclination and orientation of the surrounding facets are of importance. Another aspect for accurate physical modeling is the inclusion of the directional reflectivity. The next step to a more accurate model is therefore a 3 dimensional model (Kylling et al., 2000; Ricchiazzi and Gautier, 1998) with a resolution small enough to accurately determine the illumination effects (that depend on horizon obstruction and shading effects, orientation and inclination of the facet) on the facets. The influence of the atmospheric layer lying below the summit was not considered. Including the effects of scattering within this layer would not substantially improve the accuracy of the calculations unless other processes of similar importance, such as shading, were also taken into account. The effective albedo was calculated for all measurements obtained on March 18 and March 24 using the three methods.

On the 18 March the aerosol optical depth at 320 nm at Garmisch-Partenkirchen was as high as 0.6, which is much larger than on 24 March where even in the valley stations the aerosol optical depth was between 0.1 and 0.15. We can therefore expect a much larger uncertainty in our model calculations on 18. March. More information may be found in Gröbner et al. (2000).

3. RESULTS AND DISCUSSION

3.1 Effective albedo retrieval comparing absolute values of model calculations and spectral scans (Method 1):
The highest values were obtained at Zugspitze on both days with values around 0.55 on the 24 and 0.5 on the 18 March (Fig.2 and 3). At Wank, the effective albedo was around 0.04 – which seems rather low– on March 18 and 0.2 on March 24. In Seefeld the effective albedo was 0.18 on March 18 and 0.17 on March 24. Albedo values around 0 were automatically set to 0.03. For Oberpfaffenhofen, situated in the plains close to Munich we obtained a value near 0 which was set to 0.03. The values of effective albedo derived for the location of Murnauer Moos and Garmisch were also 0.03.

3.2 Effective albedo retrieval using model calculations and spectral slope of the scan (Method 2):
The highest values were obtained at Zugspitze and Seefeld on both days with values around 0.48 on the 18 March and 0.53 on the 24 March (Fig. 2 and 3).

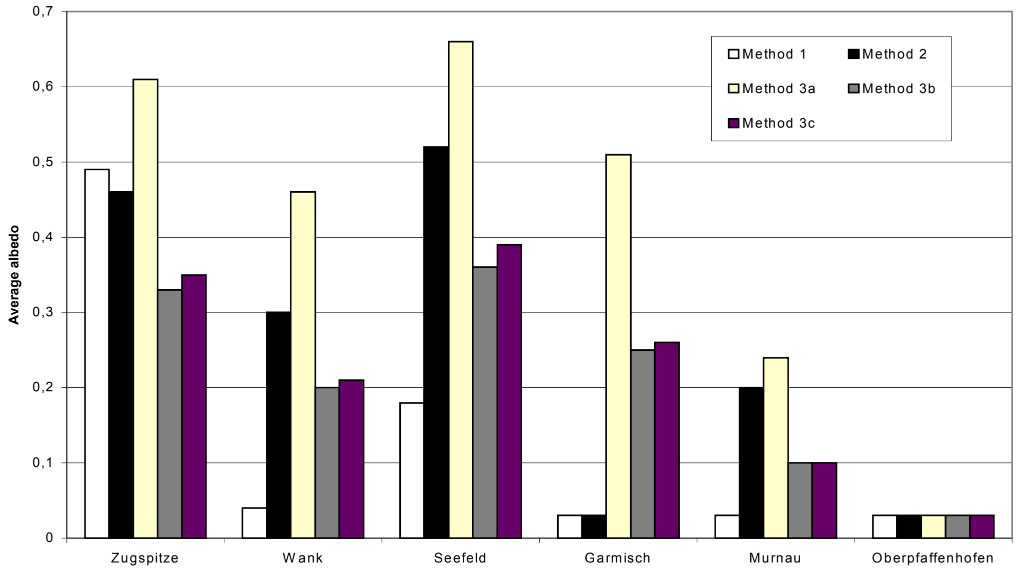

Figure 2: Daily average albedo obtained for 18 March 1999 using the 3 different methods. Values obtained with the first two methods that were below 0 were set to 0.03. The results obtained with the different methods are shown from left to right, starting with method 1 and ending with method 3c (e.g. left column = method 1; fifth column = method 3c)

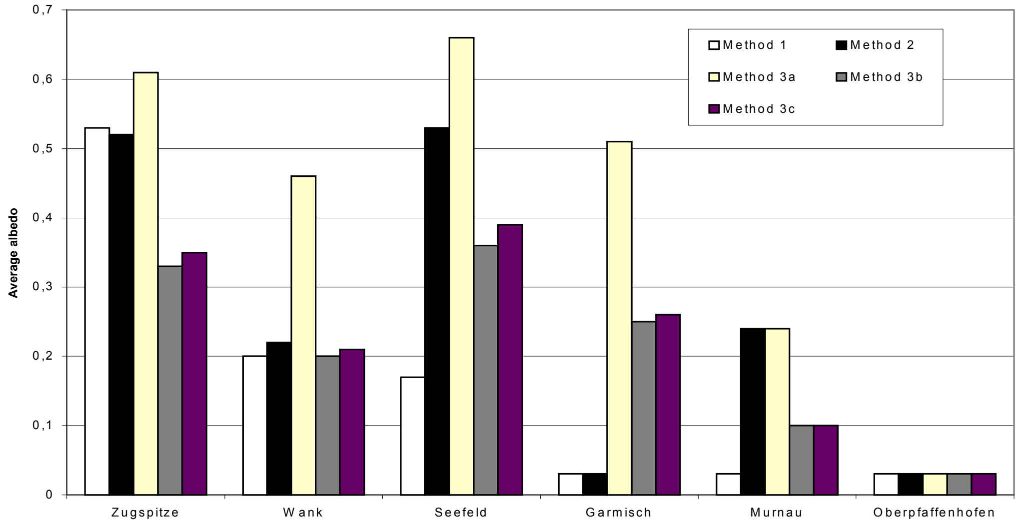

Figure 3: Daily average albedo obtained for 24 March 1999 using the 3 different methods. Values obtained with the first two methods that were below 0 were set to 0.03. The results obtained with the different methods are shown from left to right, starting with method 1 and ending with method 3c (e.g. left column = method 1; fifth column = method 3c)

At Wank, the effective albedo was around 0.3 on March 18 and 0.2 on March 24. The effective albedo at Oberpfaffenhofen, situated in the plains close to Munich, was around 0.03 as well as the effective albedo in Garmisch. The values of effective albedo derived for the location of Murnauer Moos were on both days at around 0.2.
The slightly higher effective albedo values obtained on March 24 relative to March 18 at most stations are a result of the precipitation between March 19 to March 23, during which snow fell and the snow line sank to about 700 m, increasing the overall reflectivity of the surrounding area.

3.3 Effective albedo from the method using the Digital Elevation map:
For the calculations made using the third method an assumption must be made about whether forest areas are snow covered or not. Two separate model runs were therefore performed. The first one (Method 3a) assuming snow remaining on the trees, the second one (Method 3b) assuming no snow cover on the trees. The results are shown in Fig. 2 and 3. For some places the difference in albedo for the two scenarios is up to 0.3. The largest values are for both scenarios in Seefeld and at Zugspitze. The albedo obtained for Wank is only between 0.2 and 0.46, similar to the albedo for Garmisch although the Wank site is situated at 1700 m altitude. Beside these two scenarios values for most realistic cases with forest covered with snow over 1700 m (Method 3c) were calculated for each site (Fig. 2 and 3).

3.4 Comparison of the three methods.
The results obtained with Method 1 and Method 2 are shown as a function of Method 3c (Fig. 4). According to the regression lines in fig. 3, method 2 has slightly higher values than method 3c whereas the albedos obtained with method 1 are slightly lower. The deviation in effective albedo obtained with the three methods is up to 0.3. However the correlation coefficients are 0.74 between Method 2 and Method 3c and 0.66 between Method 1 and Method 3c. According to statistical theory when 12 samples are available, a correlation is statistically significant, when it is higher or equal to 0.66. That means that Method 3c is statistically correlated with method 1 and 2. Some single values obtained with one of the Methods may however be off by up to ± 0.15.

4. DISCUSSION

Some larger discrepancies between the methods in retrieved effective albedo of up to 0.15 were found and show the limit in accuracy of these methods, which are based on very sensible instruments and models. In addition also the

sensitivity studies show that the accuracy of the effective albedo which can be reached at the moment is not better than ± 0.15. This magnitude of uncertainty causes an error in the UV irradiance calculation of approximately ± 3 to ± 5% in UVB and UVA wavelength range, respectively. To estimate the effective albedo at a given site, it is strongly advised to look at the results of different methods to estimate the effective albedo. According to the results the following conclusions can also be made:
- Differences in the effective albedo between the different stations can be attributed to differences in the snow cover of the surrounding areas.
- The effective albedo at the higher sites surrounded by snow fields is estimated to lie between 0.2 and 0.55. These are albedo values for spring conditions, however, when the valley is already snow free.
- Some sites like Garmisch-Partenkirchen showed some anomalies. The explanation for the observed discrepancies may lie, beside experimental uncertainties, in the topographical situation of Garmisch-Partenkirchen. The ground reflected radiance of a pixel depends on the illumination of the pixel and its reflectance. Many of the surrounding facets of Garmisch (where the site is in a deep valley) are frequently in the shade and may therefore reflect much less radiation.

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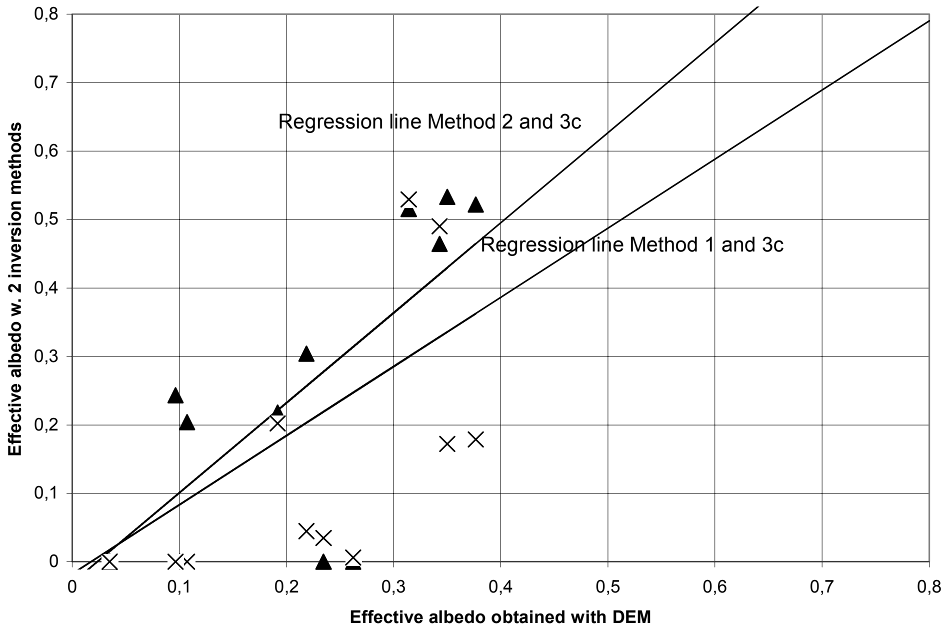

Figure 4: Effective albedo from method 1 (x) and from method 2 (▲) as a function of the albedo calculated using method 3 c (DEM map forest snow covered over 1700 m)

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