# Method to determine snow albedo values in the ultraviolet for radiative transfer modeling

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For many cases modeled and measured UV global irradiances agree to within ±5% for cloudless conditions, provided that all relevant parameters for describing the atmosphere and the surface are well known. However, for conditions with snow-covered surfaces this agreement is usually not achievable, because on the one hand the regional albedo, which has to be used in a model, is only rarely available and on the other hand UV irradiance alters with different snow cover of the surface by as much as 50%. Therefore a method is given to determine the regional albedo values for conditions with snow cover by use of a parameterization on the basis of snow depth and snow age, routinely monitored by the weather services. An algorithm is evolved by multiple linear regression between the snow data and snow-albedo values in the UV, which are determined from a best fit of modeled and measured UV irradiances for an alpine site in Europe. The resulting regional albedo values in the case of snow are in the 0.18–0.5 range. Since the constants of the regression depend on the area conditions, they have to be adapted if the method is applied for other sites. Using the algorithm for actual cases with different snow conditions improves the accuracy of modeled UV irradiances considerably. Compared with the use of an average, constant snow albedo, the use of actual albedo values, provided by the algorithm, halves the average deviations between measured and modeled UV global irradiances. © 1999 Optical Society of America

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## 1. Introduction

The observed decrease of stratospheric ozone has launched an intense discussion with regard to potential changes of the UV radiation that reaches the ground. The ozone decrease has a seasonal dependence, with reduction rates that are highest during winter and spring at northern mid-latitudes, reaching approximately 6% per decade in February.[1,2] Speculation about future ozone amounts, based on model simulations, suggests that for the next few decades ozone will remain at a low level.[3,4] Potential increases of UV radiation in spring are of particular interest, since biological effects at that time are of high relevance for humans and plants, because they are not well adapted to UV radiation. Because of the frequent snow cover at this time of the year, the estimation of actual and future dose rates by radiative transfer modeling requires a precise description of surface albedo for snow conditions. Since the fraction between snow-covered and snow-free surface is not routinely available, an algorithm is developed to determine the regional albedo for present snow cover. The expression regional albedo is used for an average albedo value for a certain area that is the relevant input value for radiative transfer models. In the values of the regional albedo all effects of the spectral dependencies of contributing areas with different local albedo, the inhomogeneity of their distribution, and the possible anisotropy are included. Routine meteorological observations are used for a parameterization of regional snow-albedo values.

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## 2. Influence of Surface Albedo on Ultraviolet Global Irradiance

Surface albedo has an influence on global irradiance, owing to scattering of radiation at the surface and to backscattering of these photons to the ground. The increase of UV spectral global irradiance that is due

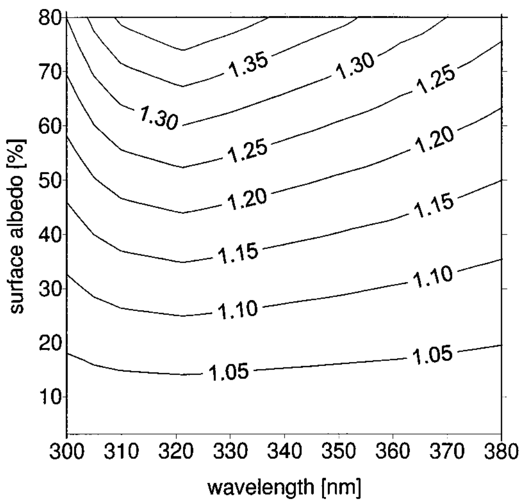

Fig. 1. Increase of spectral UV global irradiance with surface albedo compared with albedo of 0.03. The atmosphere represents 300 DU ozone and low aerosol impact (aerosol optical depth of 0.1 at 550 nm).

to an increase of a wavelength-independent surface albedo for cloudless conditions is shown in Fig. 1. The results are determined by modeling with a radiative transfer model, STAR,[5] a matrix operator model based on the discrete ordinate and adding method.[6] The atmospheric conditions were chosen to represent low aerosol impact and an ozone amount of 300 Dobson units (DU), which represents an ozone thickness of 3 mm for standard temperature and pressure conditions, also expressed by the unit of 0.3 atm cm. A change of the albedo value from 0.0 to 0.8 increases UV global irradiance by 30–40%. Even a small increase of surface albedo from 0.0 to 0.2 leads to an increase of global irradiance of more than 5%. For spectrally constant surface albedo the albedo effect increases in the UV-*A* with decreasing wavelength, because of the increase of Rayleigh backscattering. In the UV-*B* (below 320 nm) the albedo effect decreases because of the ozone absorption of the backscattered photons. Owing to the isotropic scattering of the surface, as used in the model, the albedo effects are not dependent on solar zenith angle.[7] A rough approximation of the change of UV global irradiance from $E_1$ to $E_2$ that is due to a surface-albedo variation from $A_1$ to $A_2$ is given in Eq. (1):

$$\frac{E_2 - E_1}{E_1} = 0.4(A_2 - A_1). \tag{1}$$

This formula fits best for wavelengths near 360 nm but can be used as an approximation for the entire UV wavelength range. For example, an increase of albedo by 0.4 results in an increase of UV global irradiance of 16%.

Albedo values found in the literature are usually measured by two radiometers located close to the ground, one oriented upward and one downward. Thus only a small area is considered with homogeneous properties. Such measurements for different surfaces during summer (grass, trees, asphalt, etc.) indicate that the albedo values are between 0.0 and 0.1 in the UV wavelength range.[8,9] The spectral dependence of the albedo is usually weak within the UV and generally does not exceed 0.02.[8,10,11] In the presence of snow cover, albedo values in the UV higher than 0.9 are reported for Antarctica.[12] For old snow and at urban regions the values might be slightly lower.[13,14] Measurements with high spectral resolution in the UV indicate that the spectral dependence below 400 nm seems negligible.[12] However, for use in radiative transfer models such local albedo values often are not adequate, since terrains homogeneously covered with snow do not occur. Model calculations with a three-dimensional model about the influence of albedo on UV global irradiance suggest that the effective radius around the detector for which the surface albedo has to be considered exceeds 20 km.[15] Consideration of regional albedo values is simple for snow-free conditions, because of the low variability of albedo values for different surface types. The albedo range between 0.0 and 0.1 valid for conditions with a high portion of vegetation, according to Fig. 1, affects UV global irradiance of less than 5%. Hence the assumption of a regional albedo of 0.03 for snow-free conditions is adequate for UV modeling.[16,17] For snow conditions the regional albedo is more difficult to determine, since the range of local albedo values is between ≈0.03 for snow-free terrain and ≈0.90 for clean snow. Snow-free areas can be roads, trees, roofs of buildings, etc., since they often become snow free, even during periods with snow cover. Airborne measurements of ground reflectivity give an albedo value of approximately 0.35 for a surface that is called snow covered but has a ratio of deciduous trees to pasture land of 3/2.[10] For individual situations with different snow conditions the regional albedo values can vary significantly. Thus for radiative transfer modeling specific regional albedo values have to be used for snow cover. A method to determine such values on the basis of routine meteorological observations is presented.

## 3. Method

To obtain an algorithm for the derivation of regional albedo values for conditions with snow cover, such albedo values and corresponding observed snow data are provided as input for a multiple linear regression model. This parameterization is carried out for the alpine site of Garmisch-Partenkirchen, Germany.

### A. Observed Snow Data

The regional albedo for conditions with snow cover depends to a major extent on the fraction of snow-covered and snow-free parts of the surface. Moreover, the snow albedo is also related to snow quality, in particular, to grain size and contamination with dust and soot. Therefore parameters used to determine the surface albedo for implementation in a radiative transfer model should hold some information concerning the fraction of snow cover and, if possible, the snow quality. The only information concerning snow conditions are the snow depth and the quantity of fresh fallen snow reported each morning for the previous 24 h. These observations are routinely available at the meteorological sites run by the weather service and are used in a multiple linear regression model to determine the relevant surface albedo.

### B. Regional Albedo Values in Cases of Snow Cover

The actual regional albedo is derived from the best fit between modeled and measured UV irradiances in Garmisch-Partenkirchen. The radiative transfer model STAR is used to simulate the irradiance measurements in the UV-*A*, where the uncertainties of both measurement and modeling are by far lower than in the UV-*B* wavelength region. The albedo value with the best agreement between model and measurement is used as a true value for the actual regional albedo. The regional albedo in the model is assumed to be spectrally constant and not dependent on solar zenith angle, because other assumptions must be hypothetical in any case. It is known that the spectral dependence of local albedo values in the UV wavelength range is weak. However, the effects of inhomogeneity and anisotropy on the wavelength dependence of the regional albedo are unknown. A comparison with irradiance measurements, presented later in this paper, will show whether the assumption of a spectrally constant regional albedo holds or whether the deviations between measurement and modeling will be dependent on wavelength and/or solar zenith angle.

Spectral measurements of UV irradiance have been performed at the Fraunhofer Institute in Garmisch-Partenkirchen, Germany, continually since April 1994 with approximately 100 spectra/day. The measuring site is located at 47.48 °N and 11.07 °E at 730 m above sea level. The ancillary measurements are spectral aerosol optical depth in the UV wavelength range and total ozone amount derived from measurements of the direct UV irradiance.[18,19] Two pyranometers measure the solar global irradiance and the direct component of the solar global irradiance. A nearby observational site, run by the German weather service, provides data concerning snow and cloud observations.

To obtain data for a regression between regional albedo values and snow observations, clear-sky conditions when snow cover was present are identified in a two-year data set, 1995 and 1996, with a major focus on the year 1995. Snow cover was checked by the routine observations. To avoid the influence of clouds, both the routine observation and the daily course of the direct pyranometer measurement were checked for cloudless conditions. Only days with at least half a day of cloudless conditions were used. On those days the measured clear-sky UV spectra for the smallest solar zenith angle were chosen, since the uncertainties of both measurement and model calculations are minimized.

To apply this fit for determination of the albedo values, an excellent agreement between measurement and model simulation is necessary. This can be proved for snow-free conditions when the uncertainty of surface albedo is low and the deviations between measurements and modeling should be small and free of any systematic behavior. To guarantee this high quality, the UV spectra of the years 1995 and 1996 measured at the Fraunhofer Institute under cloudless conditions when no snow cover was present were compared with model calculations. The actual barometric surface pressure, the actual ozone amount, and the actual spectral aerosol optical depth were combined with climatological means for the vertical profiles of the atmospheric constituents (pressure, temperature, humidity, ozone, aerosol extinction). As extraterrestrial solar spectrum ATLAS 3,[20] measured onboard a space shuttle mission, is used for the model calculations. We performed a simulation of the measurements by considering the true angular response of the detector within the model, where not only the direct photons but also the diffuse photons can be weighted precisely, since their angular distribution in the model is known. The restricted view to the horizon is approximated within the model by elimination of diffuse radiation coming from the direction of the mountains. The slit function of the double monochromator is simulated by a Gaussian function with a FWHM of 0.6 nm to convolute the modeled spectra to the same spectral resolution as the measurements. Since the influence of the surrounding mountains and the deviations from the ideal cosine weighting of the detector are simulated within the model, the measurements are not corrected in this regard. The measurements are corrected for a wavelength shift by use of an algorithm that analyzes the correlation between the measured spectral data and the Fraunhofer lines of the Sun.[21] In Fig. 2 the ratios between the values for 207 measured and modeled spectral global irradiances are shown for three wavelengths in the UV-*B* and the UV-*A*. Only spectra with corresponding routine observations that reported cloudless and snow-free conditions were selected. The hourly cloud observations are related to all spectra recorded between 0.5 h before and 0.5 h after. A slight zenith angle dependence of an average deviation between model and measurement of 0% for 30° and 5% for 80° solar zenith angle, comparable with those found by Mayer *et al.*[18] and with the updated comparison presented by Herman *et al.*,[22] has been corrected as well by an empirical correction term. This procedure is necessary for avoiding the misinterpretation of any systematic deviations to be an albedo effect. The correction applied here to the snow-free cases is also used below for the cases with snow cover. In the UV-*B* the ratios for the wavelength 310 nm in Fig. 2 seem to have an offset, but the high values close to 1.1 are produced mainly with data from only one day, 12 November 1995. From 4 to 10 November 1995 snow cover was reported. Probably on 12 November 1995 the remainder of the snow covered the slopes of the surrounding mountains, leading to higher measured UV irradiance.

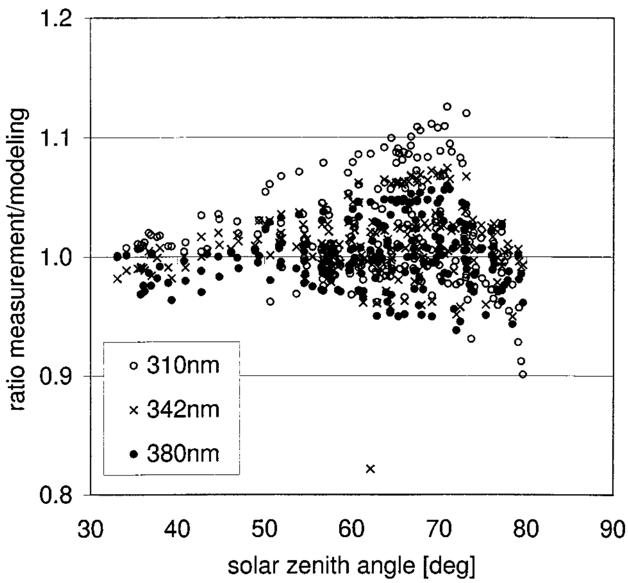


Fig. 2. Ratio between measured and modeled spectral UV global irradiance for three wavelengths (○, 310 nm; X, 342 nm; and ●, 380 nm) for cloudless and snow-free conditions.

**Table 1. Selected Albedo Values, Snow Depth, and Number of Days that Passed Since Last Fresh Fallen Snow**[a]

| Date | Albedo Value ($A$) | Snow Depth ($H$) (cm) | Number of Days ($N$) Since Last Snowfall |
|---|---|---|---|
| 24 November 1995 | 0.175 | 8 | 4 |
| 25 November 1995 | 0.225 | 8 | 5 |
| 10 December 1995 | 0.275 | 10 | 5 |
| 10 March 1995 | 0.300 | 2 | 4 |
| 05 January 1995 | 0.375 | 38 | 1 |
| 05 March 1995 | 0.400 | 17 | 0 |
| 14 January 1995 | 0.475 | 60 | 0 |
| 21 November 1995 | 0.450 | 16 | 1 |
| 16 January 1995 | 0.500 | 37 | 0 |
| 31 January 1995 | 0.500 | 54 | 2 |
| 15 January 1996 | 0.225 | 16 | 6 |
| 01 February 1996 | 0.350 | 25 | 4 |
| 05 March 1996 | 0.400 | 40 | 1 |
| 09 March 1996 | 0.200 | 30 | 5 |

[a]Albedo values are derived by best fit for the spectra for those days that could clearly be identified as having undisturbed cloudless conditions.

However, since these cases with ratios greater than 1.07 at 310 nm represent approximately 10% of all data, the average ratio between measurement and model at 310 nm for all spectra is found to be 1.02.

## 4. Results

Stable cloudless conditions of at least 12 h/day in the presence of snow cover occurred on 14 days, during the years 1995 and 1996. For the spectra at the smallest solar zenith angle on those days the model simulations were brought into agreement with the measurements by adjustment of the albedo value in the model. The results of this procedure are summarized together with the values of the routine observations in Table 1. The information concerning the fresh fallen snow during the previous 24 h was converted to information that gives the number of days that passed since the last time at least 2 cm of fresh snow fell.

The albedo values $A$, together with the corresponding snow depth $H$ (in centimeters) and the number of days that passed since the last fresh snow was falling $N$, were used for the linear regression model. $H$ varies between 2 and 60 cm, and $N$ covers the range of 0–6 days (Table 1). The result of the regression is Eq. (2):

$$A = 0.40 + 1.72 \times 10^{-3}H - 3.61 \times 10^{-2}N. \quad (2)$$

As expected, $H$ increases the surface albedo slightly and $N$ decreases it strongly. The fact that $N$ has a strong influence on $A$ is in agreement with several considerations. After fresh fallen snow, trees, roofs, and roads usually lose their total snow cover within 1 or 2 days, even if the temperatures remain cold. With increasing age of the snow surface the albedo values decrease rapidly within several days, even if the snow remains clean.[23] This albedo decrease is explained by changes in the structure of the snow crystals. Additionally, the contamination by soot, dust, etc., increases as the snow ages.

For the definition range of $H$ (2–60 cm) in combination with $N$ (0–6 days) the equation covers albedo values between 0.19 and 0.50. The coefficient of determination $r^2$ is 0.78. However, since only 14 triples of data were used, the $r^2$ value has to be rated carefully, although the $F$ statistic[24] indicates that this value for the coefficient of determination is significant on the 95% significance level. The $F$ statistic is given by

$$F = \frac{r^2}{1 - r^2}\frac{n - (k + 1)}{k}, \quad (3)$$

with the degrees of freedom $\nu_1 = k$ and $\nu_2 = n - (k + 1)$. $k$ is the number of random variables (here 2), and $n$ is the number of data points (here 14).

This significance suggests that the routine observations of the snow conditions used yield relevant information for the estimation of the actual regional albedo. We could obtain no significant improvement of the regression by taking into account other variables such as air temperature, air humidity, rainfall, etc., that might contain additional information about the snow quality. Moreover, nonlinear regressions did not give a significant improvement either. For the testing of the algorithm all spectra were used when snow cover was present and when the hourly routine observation reported cloudless conditions. Since the criterion of undisturbed daily courses of the direct pyranometer measurements was no longer required, a total number of 96 spectra could be used for the test data set. All the spectra on those days for which the algorithm was developed are excluded. A

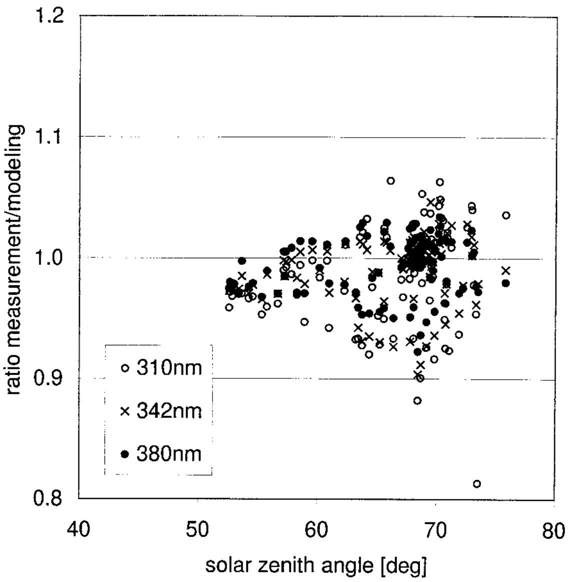


Fig. 3. Ratio between measured and modeled spectral UV global irradiance for three wavelengths (○, 310 nm; X, 342 nm; and ●, 380 nm) for cloudless conditions with present snow cover, with the albedo algorithm.

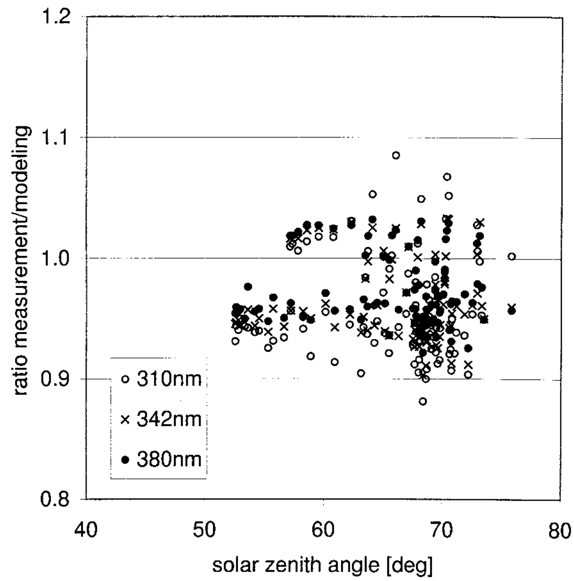


Fig. 4. Ratio between measured and modeled spectral UV global irradiance for three wavelengths (○, 310 nm; X, 342 nm; and ●, 380 nm) for cloudless conditions with present snow cover, with a constant surface albedo of 0.38 for all modeled spectra.

minimum criterion for the stability of the snow conditions during the day was considered by elimination of such cases when snow cover was reported, whereas the snow depth $H$ was 0 on the following day. The test data set is based mainly on the year 1996, when the snow conditions were significantly different from those in 1995. In 1996 long periods with no fresh fallen snow in association with cold temperatures were responsible for rather stable snow conditions in Garmisch-Partenkirchen. As a consequence, the maximum value of $N$ was set to 6, since the algorithm was developed for this range, although the periods without fresh fallen snow are sometimes longer. In Fig. 3 the agreement between modeled and measured UV global irradiance for days with snow cover in Garmisch-Partenkirchen is shown with the albedo algorithm of Eq. (2). The deviations are still generally within $\pm 5\%$ for an observed variation of surface albedo between 0.21 and 0.45. Hence, when we use the described algorithm for the parameterization of the surface albedo for conditions when snow cover is present, the agreement between model and measurement is comparable with the snow-free case.

The surface-albedo values estimated for the UV-$A$ wavelength range were applied to the UV-$B$, assuming a spectrally constant albedo for snow conditions. This assumption seems to hold roughly, because systematic deviations for the UV-$B$ wavelength range, represented by the wavelength 310 nm in Fig. 3, cannot be found. Moreover, the albedo for surfaces partially covered with snow is found to be nearly constant for different solar elevations, since no systematic deviations with solar zenith angle are evident.

## 5. Discussion

The agreement between measurements and modeling with snow-albedo values provided by the algorithm is now compared with the case in which the model calculations are carried out with a constant average albedo for all days. Of course, such an average albedo is not available in most cases. For its determination a large number of airborne measurements or detailed comparisons between measurements and model simulations are necessary. The latter have been performed in Garmisch-Partenkirchen with the result that the average albedo for present snow cover was found to be 0.38 during a two-year time series starting in April 1994 and ending in April 1996.[19] With this albedo value all spectra of the test data set in Section 4 are modeled again, and the resulting ratios between measurement and modeling results are given in Fig. 4. The deviations are slightly higher than those in Fig. 3 but still remain clearly within $\pm 10\%$. A portion of these deviations are systematic, since the average deviation in the UV-$A$ is 0.957 in Fig. 4 and 0.983 in Fig. 3. However, it can also be seen that the albedo algorithm shows the ability to deal with the individual albedo conditions on different days such that the deviations in global irradiance become smaller. The average absolute deviations versus measurements are doubled in the UV-$A$ for the average albedo model results (4–6% in Fig. 4 compared with 2–3% in Fig. 3).

The scattering range of the data as shown in Fig. 4 is related to the range of albedo values that occur. During the observed clear-sky conditions within the two years, the maximum albedo values were estimated to be near 0.5. For locations where the max-

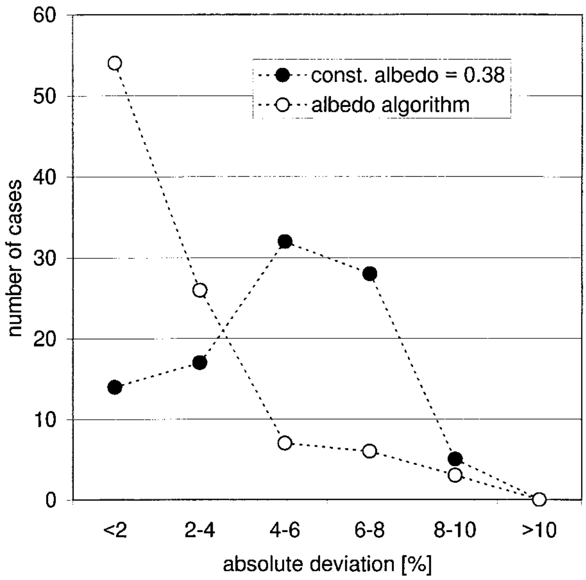


Fig. 5. Frequency distribution of absolute deviations between modeling and measurement in the UV-A wavelength range (average of the absolute deviations at 321, 342, and 380 nm) for cloud-free conditions with present snow cover (●, model calculations when the snow albedo algorithm was used; ○, calculations with a constant albedo of 0.38 for all spectra).

imum values are higher the deviations in an actual case will also increase. Because of the relatively small albedo variability found in Garmisch-Partenkirchen, it could be expected that the modeling approach with a constant albedo still yields satisfying results. To demonstrate the differences between both modeling approaches, the remaining deviations are analyzed in more detail. The absolute deviations for three wavelengths in the UV-*A* (321, 342, and 380 nm) are averaged with respect to wavelength. Their frequency distributions are shown in a histogram in Fig. 5. Whereas for constant surface albedo the maximum frequency of the deviations is near 5%, the employment of the algorithm shifts the maximum frequency to deviations smaller than 2%. The systematic deviations for the case with constant albedo contribute only marginally to the different frequency distributions. A correction of this systematic error changes Fig. 5 only slightly. If the frequencies of the absolute percentage deviations in the UV-*B* (average of the ratio measurement/modeling for the wavelengths 300, 305, and 310 nm) are compared, the effects are smaller. On the one hand the algorithm produces albedo values for the UV-*A* wavelength range that do not need to be perfectly valid for the UV-*B*. On the other hand the percentage deviations between measurement and modeling in the UV-*B* are due not only to albedo uncertainties; uncertainties in the ozone description within the model also contribute to the observed differences.

## 6. Conclusion

A method to parameterize regional albedo values in the case of snow for use in a radiative transfer model is presented. A multiple linear regression model is applied that is able to explain most (in the example, 78%) of the observed variation in albedo values. The application of the regression algorithm to an independent test data set showed that the resulting deviations between measured and modeled UV global irradiances for conditions with snow cover are not significantly higher than for snow-free conditions. Although the snow conditions in the test data set were completely different from those for which the algorithm was developed, no significant overestimation or underestimation of albedo values could be observed. The assumption of a regional albedo in cases of snow cover that is independent of wavelength within the UV and of solar zenith angle seems to hold for the site of Garmisch-Partenkirchen.

The comparison between measured and modeled UV spectra for cloud-free conditions when snow cover is present, with an average surface albedo, gives reasonable results as well. However, this good agreement between modeling and measurements may change for other locations where maximum values of surface albedo, and consequently the range of variation, are higher. The knowledge of a reliable average surface-albedo value is not available in most cases. Consequently, snow-albedo values from the literature are generally used. The employment of local albedo values near 0.8 that are commonly found in the literature overestimates the regional albedo considerably, because the snow cover is not continuous in most cases. For the example of Garmisch-Partenkirchen, the usage of such an albedo value leads to systematic deviations between measurement and modeling of approximately 20%, estimated on the basis of Eq. (1). It can be concluded that the regional albedo relevant for UV modeling is much less than the values usually given in the literature for snow. However, the results of Doda and Green,[10] derived by aircraft measurements, and which thus describe regional albedos, give a value of 0.35 for snow-covered ground, which is in good agreement with the results found here for Garmisch-Partenkirchen.

The parameters used for the surface-albedo estimation depend on the area conditions. The fraction between snow-covered and snow-free surface is related to the portion of trees, houses, roads, etc. The snow quality depends on environmental conditions such as pollution. Therefore the constants of the regression may need to be adapted if the algorithm is used for areas different from Garmisch-Partenkirchen.

The derivation of snow-albedo values with the introduced method is not restricted to cloudless atmospheres. For cloudy conditions the use of correct albedo values is even more essential for radiative transfer modeling, because of the enhanced backscattering of photons reflected at the surface.

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## References


1. U. Köhler, W. Vandersee, and P. Winkler, "Spektrale und integrale Messungen der UV-B-Strahlung im Vergleich zu Ozonmessungen," final Rep. of the Bayerisches Klimaforschungsprogramm project BI 10 (Deutscher Wetterdienst, Meteorologische Observatorium, Hohenpeissenberg, 1995).
2. S. Chandra, C. Varotsos, and L. E. Flynn, "The mid-latitude total ozone trends in the northern hemisphere," Geophys. Res. Lett. **23,** 555–558 (1996).
3. D. T. Shindell, D. Rind, and P. Lonergan, "Increased stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations," Nature (London) **392** 589–592 (1998).
4. M. Dameris, V. Grewe, R. Hein, C. Schnadt, C. Brühl, and B. Steil, "Assessment of the future development of the ozone layer," Geophys. Res. Lett. **25,** 3579–3582 (1998).
5. A. Ruggaber, R. Dlugi, and T. Nakajima, "Modelling radiation quantities and photolysis frequencies in the troposphere," J. Atmos. Chem. **18,** 171–210 (1994).
6. T. Nakajima and M. Tanaka, "Algorithms for radiative intensity calculations in moderately thick atmospheres using a truncation approximation," J. Quant. Spectrosc. Radiat. Transfer **40,** 51–69 (1988).
7. H. Schwander, P. Koepke, and A. Ruggaber, "Uncertainties in modeled UV-irradiances due to limited accuracy and availability of input data," J. Geophys. Res. **102,** 9419–9429 (1997).
8. M. Blumthaler and W. Ambach, "Solar UVB-albedo of various surfaces," Photochem. Photobiol. **48,** 85–88 (1988).
9. S. Madronich, "UV radiation in the natural and perturbed atmosphere," in *UV-B Radiation and Ozone Depletion, Effects on Humans, Animals, Plants, Microorganisms, and Materials*, M. Tevini, ed. (Lewis Publishers, Boca Raton, Fla., 1993), pp. 17–71.
10. D. D. Doda and A. E. S. Green, "Surface reflectance measurements in the UV from an airborne platform. Part 1," Appl. Opt. **19,** 2140–2145 (1980); "Surface reflectance measurements in the ultraviolet from an airborne platform. Part 2," Appl. Opt. **20,** 636–642 (1980).
11. R. L. McKenzie, M. Kotcamp, and W. Ireland, "Upwelling UV spectral irradiances and surface albedo measurements at Lauder, New Zealand," Geophys. Res. Lett. **23,** 1757–1760 (1996).
12. T. C. Grenfell, S. G. Warren, and P. C. Mullen, "Reflection of solar radiation by the antarctic snow surface at ultraviolet, visible and near-infrared wavelengths," J. Geophys. Res. **99,** 18,669–18,684 (1994).
13. P. Chýlek, V. Ramaswamy, and V. Srivastava, "Albedo of soot-contaminated snow," J. Geophys. Res. **88,** 10,837–10,843 (1983).
14. F. D. Eaton and I. Dirmhirn, "Reflected irradiance indicatrices of normal surfaces and their effect on albedo," Appl. Opt. **18,** 994–1008 (1979).
15. M. Deguenther, R. Meerkoetter, A. Albold, and G. Seckmeyer, "Case study on the influence of inhomogeneous surface albedo on UV irradiance," Geophys. Res. Lett. **25,** 3587–3590 (1998).
16. P. Wang and J. Lenoble, "Comparison between measurements and modeling of UV-B irradiance for clear sky: a case study," Appl. Opt. **33,** 3964–3971 (1994).
17. J. Zeng, R. McKenzie, K. Stamnes, M. Wineland, and J. Rosen, "Measured UV spectra compared with discrete ordinate method simulations," J. Geophys. Res. **99,** 23,019–23,030 (1994).
18. B. Mayer, G. Seckmeyer, and A. Kylling, "Systematic long-term comparison of spectral UV measurements and UVSPEC modeling results," J. Geophys. Res. **102,** 8755–8767 (1997).
19. B. Mayer and G. Seckmeyer, "Retrieving ozone columns from spectral direct and global UV irradiance measurements," presented at the XVIII Quadrennial Ozone Symposium, University of L'Aquila, L'Aquila, Italy, 12–21 September 1996.
20. M. VanHoosier (Naval Research Laboratory, Washington, D.C., personal communication, 1996). The solar spectrum is available by ftp from ftp://susim.nrl.navy.mil/pub/atlas3.
21. B. Mayer, "Messung und Modellierung der spektralen UV-Bestrahlungsstärke in Garmisch-Partenkirchen," IfU-Schriftenreihe, 45-97 (Fraunhofer Institute for Atmospheric Environmental Research, Garmisch-Partenkirchen, Germany, 1997).
22. J. Herman, R. L. McKenzie, S. B. Diaz, J. B. Kerr, and G. Seckmeyer, "Surface ultraviolet radiation," in *Scientific Assessment of Ozone Depletion 1998*, World Meteorlogical Organization, Global Ozone Research and Monitoring Project Rep. 37 (United Nations Environmental Program, P.O. Box 30552, Nairobi, Kenya, 1998), Chap. 9.
23. W. Ambach and H. Eisner, "Albedo verschiedener Schneeoberflächen für erythemwirksame solare Strahlung," Wetter Leben **38,** 1–4 (1986).
24. A. Sen and M. Srivastava (*Regression Analysis, Theory, Methods and Applications* Springer, New York, 1994).