GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO.4, PAGES 397-400, FEBRUARY 15, 1997

# Transmittance of a cloud is wavelength–dependent in the UV–range: Physical interpretation

A. Kylling

NORUT Information Technology, N-9005 Tromsø, Norway.

A. Albold and G. Seckmeyer

Fraunhofer Institute for Atmospheric Environmental Research, Garmisch-Partenkirchen, Germany

**Abstract.** In the recently published GRL paper by Seckmeyer et al. [1996] an example of a cloud that has a wavelength dependent effect on the surface UV–radiation is given. Through careful and accurate radiative transfer modelling, the present paper aims to give a physical interpretation of the reported wavelength dependence of this particular cloud. The modelling shows that the transmission of the cloud alone does not vary significantly with wavelength in the UV. However, the cloud gives a wavelength dependent effect in the surface UV–radiation due to radiation scattered upwards from the cloud and then scattered downwards again, effectively trying to make it through the cloud more than once. The number of photons this happens to is a function of the wavelength dependent Rayleigh scattering and ozone absorption cross sections.

## Introduction

Seckmeyer et al. [1996] have reported the spectral attenuation of the UV–irradiance by a homogeneous cloud layer at an altitude of about 1200 m. Two measurement stations, one above the cloud at the top of Zugspitze (2964 m a.s.l.) and one below the cloud at the Fraunhofer–Institute for Atmospheric Environmental Research (730 m a.s.l.), measured the spectral irradiance on the cloudy day (22nd of October 1995) and on a nearby clear day (24th of October 1995). Seckmeyer et al. [1996] calculated a spectral transmittance by forming "the ratio of the global spectral irradiance beneath a homogeneous cloud–cover to the global spectral irradiance on a clearsky day". Furthermore, "The transmittance of the cloud–layer was found to be wavelength–dependent, ranging from 45% in the UVA to 60% in the UVB. Therefore, it can be assumed that clouds are not generally "grey" (i.e. that the attenuation is dependent on wavelength)", [Seckmeyer et al. 1996].

Theoretical studies have also noticed an increase of the cloud transmittance below 400 nm, followed by a decrease below 320 nm [Frederick and Lubin, 1988; Wang and Lenoble, 1996]. However, the increase between 380 nm and 320 nm in the cloud transmittance reported by these studies is smaller than that measured by Seckmeyer et al. [1996]. Frederick and Lubin [1988] report nearly constant values for the cloud transmittance between 320 nm and 400 nm, while Wang and Lenoble [1996] report a cloud transmittance of 0.5 (0.57) at 320 (400) nm for a cloud of optical depth 10. It is emphasized that the values used in these studies for the solar zenith angle, surface albedo, altitude, ozone column etc. are different from those encountered during the measurements reported by Seckmeyer et al. [1996].

In this paper a well documented and tested radiative transfer program is used to model the measured radiation field at Garmisch–Partenkirchen and Zugspitze on the cloudy and the clear day. Next, the model is used to provide additional information that is not measured. This information, in combination with the measurements, is then used to give a physical interpretation of the reported wavelength dependence of the cloud transmittance.

## Model description and results

Noon-time global irradiances were calculated at Garmisch–Partenkirchen and Zugspitze for the respective days, and atmospheric conditions. The discrete ordinate method developed by Stamnes et al. [1988] was used to solve the radiative transfer equation. Ozone cross sections were from Daumont et al. [1992] and the extraterrestrial spectrum from the SUSIM instrument onboard the space shuttle during the ATLAS 2 mission in 1993 [Woods et al., 1996]. It was modified to account for the slit function of the spectroradiometers. The wavelength resolution of the model is 1 nm.

The ozone profile was taken from the midlatitude winter atmosphere model of Anderson et al. [1987]. It was scaled to the ozone column measured on Zugzpitze (ZUG), 254 and 266 DU on the 22nd and 24th respectively. No direct observation of the ozone column was available for Garmisch–Partenkirchen on the cloudy day, the 22nd. The ozone column in Garmisch–Partenkirchen (GAR) on the 22nd was estimated to be $O_3$[GAR cloudy] = $O_3$[GAR clear]-($O_3$[ZUG clear]-



Paper number 97GL00111
0094-8534/97/97GL-00111$05.00

$O_3$[ZUG cloudy]) = 264 DU. For the 24th Seckmeyer et al. [1996] reported an ozone value of 279 DU. In the model calculations presented below a value of 276 DU is adopted. This value gives a better agreement between model and measurement for wavelengths shorter than 305 nm. It is within the uncertainties in the ozone column estimation method used [Mayer and Seckmeyer, 1996]. The model atmosphere used for Zugspitze was truncated at 2964 m, while the model atmosphere used for Garmisch–Partenkirchen went down to 730 m.

The surface albedo was taken to be 0.5 for Zugspitze on the 24th and 0.57 on the 22nd. The larger value for the surface albedo on the 22nd is used to account for the increased backscattering by the cloud below the summit. The adopted values gave the overall best agreement between measured and modelled global irradiances, see Figure 1 for Zugspitze on the 22nd. For the various surfaces found in Garmisch–Partenkirchen in the summertime the surface albedo is smaller than 0.05 in the UV-region [Blumthaler et al. 1996]. A value of 0.0 was adopted for the surface albedo in Garmisch–Partenkirchen for both days.

The cloud on the 22nd was assumed to be homogeneous and situated between 1200 and 1350 m [Seckmeyer et al., 1996]. The parameterization due to Hu and Stamnes [1993] was used to calculate the cloud optical properties. The liquid water content was set to 0.485 g/m$^3$, and the effective droplet radius to 10.0 $\mu$m giving a cloud optical depth of 11.24 (11.28), single scattering albedo of 0.9998 (1.0) and asymmetry factor of 0.8668 (0.8654) at 300 nm (400 nm). The liquid water content was adopted to get an overall best agreement between measured and modelled spectra, see Figure 1. It is noted that other combinations of the liquid water content and the effective droplet radius may also be used to reproduce the measurement on the cloudy day, e.g. an effective droplet radius of 20.0 $\mu$m and a liquid water content of 1.1 g/m$^3$. However, using other realistic combinations of these two parameters have negligible effect on the wavelength dependence of the optical depth, the single scattering albedo and the asymmetry factor of the cloud [Hu and Stamnes, 1993]. Small effective droplet radiuses, i.e. 2.0 $\mu$m, are unrealisticly low for stratus clouds [Pruppacher and Klett, 1978] and will result in a different wavelength dependence than that reported by Seckmeyer et al. [1996].

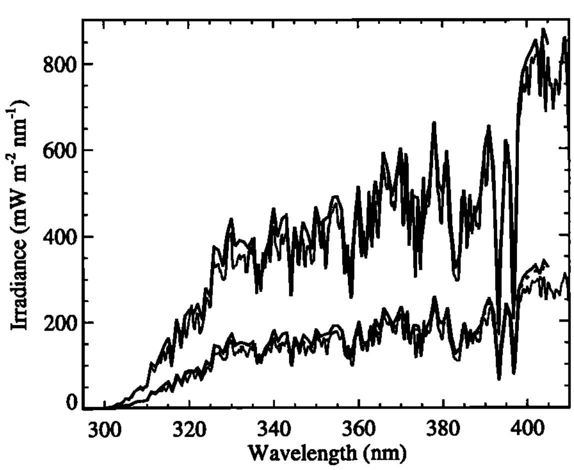


**Figure 1.** Spectral global irradiance at Zugspitze (upper two curves) and Garmisch (lower two curves) on the 22nd of October. Thin line: averaged measurements; thick line: noon time model results.

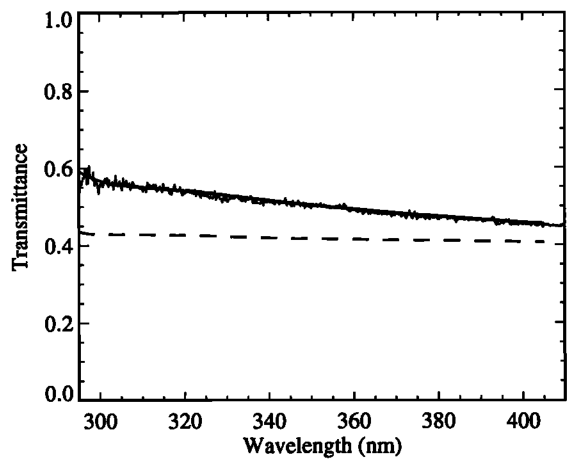


**Figure 2.** The cloud transmittance as defined by Equation 1, thin solid line (measurement, Seckmeyer et al. [1996]), thick solid line (model). The thick dashed line (model) is the transmission of the cloud alone as defined by Equation 2.

The accuracy of the modelled spectra relative to the measurements are within ±10% [Mayer et al., 1997].

Having reproduced the measured spectra the cloud transmittance, $\Upsilon$, as defined by Seckmeyer et al. [1996] ('cloudy day' and 'clear day' refer to the downward flux at Garmisch–Partenkirchen on the 22nd and 24th of October respectively):

$$\Upsilon = \left(\frac{\text{cloudy day (22nd)}}{\text{clear day (24th)}}\right)\left(\text{ozone correction}\right) \quad (1)$$

is accurately reproduced by the model, see Figure 2. Hence, the model reproduces the measured wavelength dependence in the surface UV radiation due to the presence of the cloud. The ratio of the spectral global irradiance at Zugspitze on the 22nd and the 24th, i.e. the ozone correction term, is also accurately reproduced by the model, see Figure 3.

## Interpretation of the cloud effect

The transmission, $T$, of the cloud alone is defined as

$$T = \frac{\text{downward flux below cloud}}{\text{downward flux at top of cloud}}. \quad (2)$$

Unfortunately, measurements of the downward flux at the cloud top and bottom are not available, nor would such measurements be easy to make. However, with the model, the cloud transmission as defined by Equation 2 may be calculated, see Figure 2, thick dashed line.

The cloud transmission $T$ exhibits only a very small wavelength dependence. It is due to the wavelength dependence of the Mie scattering of radiation within the cloud. Hence, the wavelength dependence in the transmittance $\Upsilon$ is not due to the traversal of the cloud by the photons.

However, the cloud will increase the upward flux of photons above the cloud, effectively increasing the planetary albedo. Some of these photons will be backscattered in the downward direction. Hence, on the cloudy day there will be an increased downward flux of radiation at the cloud top. To quantify the increased downward flux, a clear sky model calculation was carried out for the 22nd of October. In Figure 4 is shown the ratio between the cloudy and clear sky downward flux at the cloud top and at Zugspitze.

The overall increase in the magnitude of the downward flux on the cloudy day is, as expected, more pronounced at the cloud top than at Zugspitze. The wavelength dependence of the ratio is caused by two contributing effects: (1) the dominant Rayleigh scattering above 320 nm, where the flux increases with decreasing wavelength; and (2) the ozone absorption, primarily below 320 nm, where the absorption reduces the increase in the downward flux, ultimately reversing the slope effect with wavelength.

Multiplying the cloud transmission $T$ with the cloudy/clear ratio at the cloud top gives the cloud transmittance $\Upsilon$ for wavelengths larger then 320 nm. For shorter wavelengths (than 320 nm) ozone absorption complicates the picture, both due to the different ozone columns on the two days and the ozone correction factor in Equation 1.

## Conclusion

With the assumptions made for the surface albedo at Zugspitze and the optical properties of the water cloud, the measured spectra in Garmisch–Partenkirchen and on Zugspitze are reproduced by the model calculations. From the model calculations it is concluded that the wavelength dependence seen in the surface UV–radiation due to the presence of the cloud, is not caused by processes happening to photons while they are *transmitted* through the cloud. Rather, the effect is caused by photons *reflected* upward by the cloud, then scattered downward again by the atmosphere above the cloud. Hence, the observed wavelength dependence is a result of the presence of the cloud and due to Rayleigh scattering above the cloud.

The present physical interpretation applies to the cloud results presented by Seckmeyer et al. [1996]. It may not necessarily be valid for other cloudy situations.

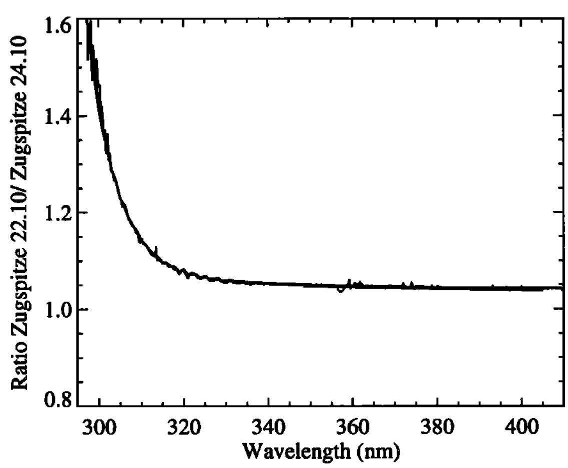


**Figure 3.** Ratio of spectral global irradiance at Zugspitze on the 22nd and the 24th of October 1995. Thin line: averaged measurements; thick line: noon time model results.

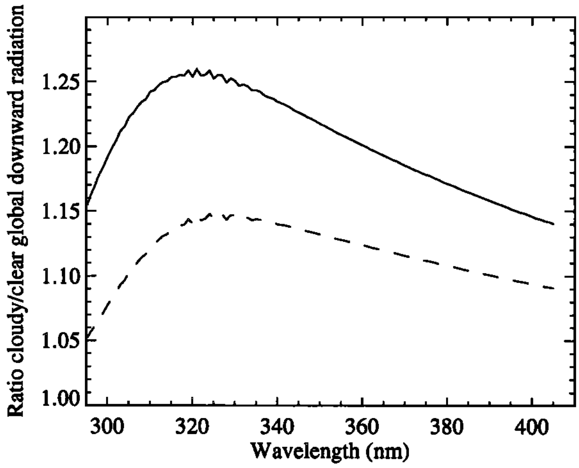


**Figure 4.** The cloudy/clear model ratio of the global flux at the altitude of the cloud top (solid line) and at the altitude of Zugspitze (dashed line).

**Acknowledgments.** We would like to thank Bernhard Mayer for providing data essential for the modelling. This work has been funded by the German ministry of Education, Science, Research and Technology (BMBF), the Deutsche Bundesstiftung Umwelt (DBU) and the Commission of European Communities within the framework of the SUVDAMA project. Information about the cloud cover was given by the German Weather Service (DWD). One of us (A.K.) would like to thank the Norwegian Research Council for partial support.

## References

Anderson, G. P., S. A. Clough, F. X. Kneizys, J. H. Chetwynd and E. P. Shettle, AFGL Atmospheric Constituent Profiles (0–120 km), *Rep. AFGL-TR-86-0110*, AFGL (OPI), Hanscom AFB, MA 01736, 1987.

Blumthaler, M., and W. Ambach, Solar UVB-albedo of various surfaces. *Photochemistry and Photobiology, 48*, 85–88, 1988.

Daumont, D., J. Brion, J. Charbonnier, and, J. Malicet, Ozone UV Spectroscopy I: Absorption Cross-Sections at Room Temperature, *J. of Atmos. Chem., 15*, 145–155, 1992.

Frederick, J. E., and D. Lubin, The budget of biologically active ultraviolet radiation in the Earth-atmosphere system, J. Geophys. Res., *93*, 3825–3832, 1988.

Hu, Y.X. and K. Stamnes, An accurate parameterization of the radiative properties of water clouds suitable for use in climate models, *J. Climate*, *6*, 728–742, 1993.

Mayer, B., and G. Seckmeyer, Retrieving Ozone Columns from Spectral Direct and Global UV Irradiance Measurements, in Proceedings of the XVIII Quadrennial Ozone Symposium, L'Aquila, 1996.

Mayer, B., G. Seckmeyer and A. Kylling, 'Systematic longterm comparison of spectral UV measurements and UVSPEC modelling results', J. Geophys. Res., in press 1997.

Pruppacher H., Klett J., *Microphysics of Clouds and Precipitation*, D.Reidel Publishing Company, Dordrecht Holland, (ISBN 90-277-01515-1), 1978.

Seckmeyer, G., R. Erb, and A. Albold, Transmittance of a cloud is wavelength–dependent in the UV–range, Geophys. Res. Lett., *23*, 2753–2755, 1996.

Stamnes, K., S.-C. Tsay, W. Wiscombe and K. Jayaweera, Numerically stable algorithm for discrete–ordinate–method radiative transfer in multiple scattering and emitting layered media, *Applied Optics*, *27*, 2502–2509, 1988.

Wang, P., and J. Lenoble, Influence of clouds on UV irradiance at ground level and backscattered exittance, *Adv. Atmos. Sci.*, *13*, 217–228, 1996.

Woods, T. N., D. K. Prinz, G. J. Rottman, J. London, P. C. Crane, R. P. Cebula, E. Hilsenrath, G. E. Brueckner, M. D. Andrews, O. R. White, M. W. VanHoosier, L. E. Floyd, L. C. Herring, B. G. Knapp, C. K. Pankratz, and, P. A. Reiser, Validation of the UARS solar ultraviolet irradiances: Comparison with the ATLAS 1 and 2 measurements, J. Geophys. Res., *101*, 9541–9569, 1996.

A. Kylling, NORUT Information Technology, N-9005 Tromsø, Norway; phone: +47 77 62 94 37, fax: +47 77 62 94 01, email: arve.kylling@itek.norut.no

A. Albold and G. Seckmeyer, Fraunhofer Institute for Atmospheric Environmental Research, Kreuzeckbahnstrasse 19, D-82467 Garmisch-Partenkirchen, Germany; phone: +49 8821 183 166, fax: +49 8821 183 295, email: uvb@ifu.fhg.de

(received November 25, 1996; accepted December 27, 1996.)