GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 4, PAGES 721-724, FEBRUARY 15, 2001

The Ring Effect in the cloudy atmosphere

R. de Beek, M. Vountas, V. V. Rozanov, A. Richter, and J. P. Burrows

Institute of Environmental Physics, University of Bremen, Bremen, Germany

Abstract. Filling-in of spectral features observed in scattered sunlight and known as the “Ring Effect” has a significant impact on the retrieval of atmospheric trace constituents from both ground-based and satellite observations. As clouds also have strong impacts on radiative transfer in the UV/visible spectral range, possible changes of the Ring Effect due to clouds have to be considered. Such investigations require radiative transfer modeling explicitly accounting for both cloud and Ring features. UV/visible ground and satellite based measurements, taken under cloudy conditions, were used to validate Ring and cloud modeling using the radiative transfer model SCIATRAN. As an example results of model applications are presented for both ground-based and satellite geometry. Two case studies are used to explain the sources of the observed Filling-in.

1. Introduction

The fact that the depth of solar Fraunhofer lines in scattered light is less than that observed in direct sunlight, was discovered by *Shefov* [1959] and *Grainger and Ring* [1962] and is known as “Ring Effect” or “Filling-in”. Analyses of the origins of this effect have shown that rotational Raman scattering provides the dominant contribution (e.g. *Kattawar et al.* [1981], *Vountas et al.* [1998] and references therein). The majority of these studies however concentrated on cloud-free conditions.

Detailed investigations of the effect of trace gas absorption and particle and cloud scattering require a radiative transfer model, including Filling-in (e.g. *Kattawar et al.* [1981]). *Vountas et al.* [1998] introduced a new approach to accurately calculate Filling-in using the radiative transfer model SCIATRAN (formerly GOMETRAN) [*Rozanov et al.*, 1997]. They demonstrated that by taking rotational Raman scattering into account within the radiative transfer processing, Filling-in of Fraunhofer and gas absorption features for cloud-free conditions is modeled with a high accuracy. SCIATRAN is also able to model clouds assuming that radiative transfer in the presence of clouds is adequately described by Mie-scattering and using semi infinite layers or an effective reflecting boundary [*Kurosu et al.*, 1997]. Clouds do affect Filling-in due to contributions of both Mie- and Rayleigh-scattering, e.g. influences of multiple scattering on the slant path of the light. Although polarisation is not explicitly taken into account and viewing geometries are restricted to where the semi infinite horizontal cloud approximation is reasonable, the Ring Effect arising from clouds can be well investigated for both ground and satellite geometry using SCIATRAN.

In this study radiances between 390 nm and 400 nm were calculated and compared to those from ground and satellite borne observations for cloudy conditions. Examples of model applications for both viewing geometries consider Filling-in in the same spectral region. The main objective of the study is to determine whether our current understanding of the Ring Effect explains spectral structures appearing in the considered cloud observations.

2. Ring Modeling and its Validation

Measurements made by the Global Ozone Monitoring Experiment GOME [*Burrows et al.*, 1999] and a ground-based zenith-sky spectrometer [*Richter*, 1997] were selected for comparison with radiances simulated by SCIATRAN. The spectral range between 390 and 400 nm has been selected as a test region containing only weak gaseous absorption and two strong solar Fraunhofer lines, which are the Ca II-lines, located at 393.37 nm and 396.85 nm. A solar irradiance spectrum I_0 is required for simulation of Filling-in structures. For this purpose the high resolution solar spectrum measured by *Kurucz et al.* [1984], convolved with the proper instrument functions, was used.

If I specifies the atmospheric radiance, the Differential Optical Depths, DOD, is defined as $DOD = -\ln\left(I/I_{ref}\right) - P$, where for the satellite case, $I_{ref} = I_0$. For ground-based measurements, where the solar irradiance is not available, radiances observed under clear sky conditions near noon, where the optical light path is relatively small, are used as reference I_{ref}. A third degree polynomial P accounts for broadband features in the selected spectral region. For both ground and satellite viewing geometries, DODs were determined by a least squares fitting procedure, which also accounts for minor instrumental spectral drifts. The DOD for simulated rotational Raman and the extracted Ring Effect could then be compared.

The Ring spectrum R is defined by $R = \ln\left(I^+/I^-\right)$ [*Vountas et al.*, 1998], where for the calculation of the radiance I^+ rotational Raman scattering is included and for I^- it is not. DOD can be described as $DOD = -\ln\left(I^-/I_{ref}\right) - P - R$. For ground-based observations R is calculated for the difference between Filling-in of the measured spectrum and the reference spectrum. Remembering that broadband features cancel out, it can be seen that, excluding gaseous absorption, R can explain the observed DOD and is called “Ring DOD” in the following. From the approximation $R \approx \Delta I/I^-$, where $\Delta I = I^+ - I^-$ is the Raman-scattering contribution, it can be concluded that both the Raman contribution ΔI and the intensity of the Mie-scatted radiance I^- alter the Ring DOD.

2.1. Ground-based Situation

Ground-based UV/visible zenith sky measurements were made on the 13th and on the 15th June 1996 at Observa-

Paper number 2000GL012240.
0094-8276/01/2000GL012240$05.00

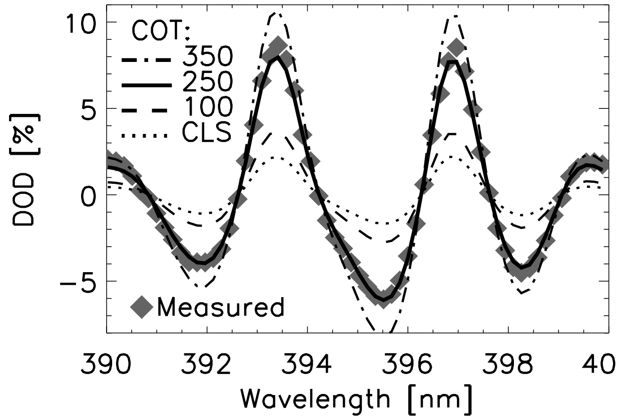

Figure 1. Differential optical depths (DOD) derived from ground-based measurements on the 15th of June 1996 at Observatoire d'Haute Provence. Observations were made under a thunderstorm cloud (18:58 h UTC, solar zenith angle 77.75°). Measurements are compared with calculated DODs using a cumulonimbus cloud type and different optical thicknesses (COT; CLS: clear sky). Geometrical cloud parameters were used as given by *Winterrath et al. [1999]*.

toire d'Haute Provence, France (see *Roscoe et al.* [1999] and *Winterrath et al.* [1999] and references therein). On both days thunderstorm events were observed and these periods are one focus of this study. Modeled DODs are adequately determined assuming a cumulonimbus cloud type. The average cloud height range for the thunderstorm on 15th June between 5:30 h and 8 h pm was derived by *Winterrath et al.* [1999]. A number of cloud optical thicknesses (COT) were applied for the cloud height range (1.8 km to 10.8 km) assuming a cumulonimbus cloud type having constant particle density. Fig. 1 shows DODs derived from both calculations and measurement. NO_2 DOD were fitted and subtracted from the total DOD to yield measured Ring DOD for comparison with simulated Ring DOD. (Consequences of the thunderstorm for production of NO_2 have been discussed by *Winterrath et al.* [1999].) In contrast, for the cloud-free case NO_2 absorption structures can to a very good first order approximation be neglected in this spectral range. For the different COTs considered varying DODs were calculated. The use of COT=250 matches the measured DOD to a good approximation. Fig. 1 shows that the thunderstorm cloud leads to strong increase of Filling-in compared to the cloud-free case.

As an example of model application Ring DODs were calculated for both simulated and measured spectra observed on the 13th June 1996. Solar zenith angles and cloud conditions described by *Richter* [1997] were used for simulations, including modeling of the reference spectrum I_{ref}. Ring DODs were retrieved from the observed spectra between 390 and 400 nm using the DOAS technique (Differential Optical Absorption Spectroscopy [*Platt and Perner*, 1980]). Following clear sky conditions early afternoon, a thunderstorm crossed the measurement site between 3 and 5 pm, followed by altostratus between 5 pm and dusk. Two cloud types were therefore simulated: Cumulonimbus having a COT of 150 and extending from 1.5 to 5 km and altostratus having a COT of 10 and extending from 2 to 2.5 km. Ring DODs at 393.37 nm are compared in Fig. 2 without applying a numerical fitting procedure. The curve for a clear day (June 19) is also plotted along with clear sky simulations. The Ring DODs observed are well reproduced by the model for both clear sky and cloud conditions. Ignoring the short decrease of Ring DOD in the beginning of the thunderstorm and similar small scale structures, which can be related to horizontal inhomogeneities not discussed here, modeled and measured Ring DODs increase relative to the clear day Ring as the thunderstorm appears. For following altostratus clouds the Ring DOD decreases.

Explanation: For ground-based measurements, light detected when observing the zenith sky has passed through the entire atmosphere and the cloud. Two processes influence Filling-in: Enhancement of the light path due to multiple scattering inside the cloud, implying a growing number of collisions of light photons with air molecules and therefore increasing Rayleigh- and Raman-scattering contributions ΔI. On the other hand compared to the clear sky, light is either scattered into the instrument or diminished by Mie-scattering at cloud particles, leading to varying intensities I^-. The observed increase of radiance by Mie-scattering in case of thin clouds therefore weakens Filling-in compared to the clear sky. In an optically thick thunderstorm cloud, long optical paths occur combined with a strong decrease of detected light. Therefore ΔI then dominates over I^- in the above definition of R, leading to enhanced Filling-in. The intersection of the clear sky and cloud curves after the thunderstorm shows that compared to the clear sky processes due to clouds are able to compensate the Filling-in when observed from ground.

2.2. Comparison with Satellite Measurements

For this investigation, earthshine upwelling radiance and the extraterrestrial solar irradiance measured by GOME were used. A specific GOME scene, measured at 43.23N, 27.44W, at 12.52 h UTC on the 15th October 1996 above the Atlantic ocean, was selected. According to the GOME cloud coverage data, this ground pixel was completely covered with clouds. An average cloud-top height (CTH) for the scene was derived from cloud-top temperatures using Meteosat data, recorded at 12.00 h UTC and temperature measurements of a balloon sonde, launched by the German research ship Polarstern at 42 N, 35 W, at 10.18 h UTC. Com-

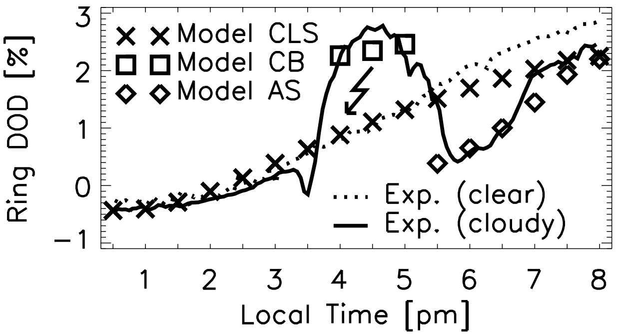

Figure 2. A comparison of Ring DODs for the Ca II-line at 393.37 nm calculated using ground-based spectra observed at the Observatoire d'Haute Provence on the 13th (Thunderstorm symbol) and 19th of June 1996 (nearly clear day) and SCIATRAN with clear day (CLS), cumulonimbus (CB, 4-5 h pm, COT=150) and altostratus cloud conditions (AS, 5:30-8 h pm, COT=10). The experimental random error can be neglected (below 0.1 units). Explanations: see text.

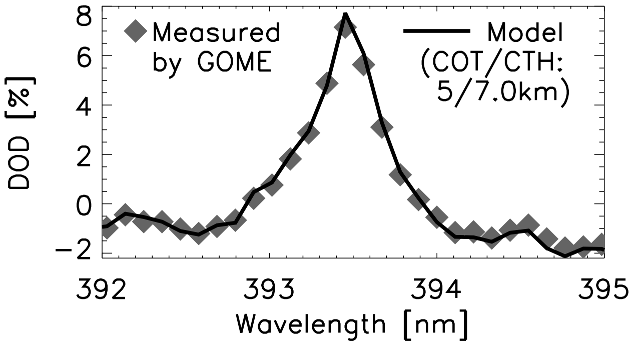

Figure 3. Diff. opt. depths (DOD) derived for the spectral range from 390 nm to 400 nm from a GOME observation on the 15th October 1996 at 43.23 N, 27.44 W, 12.52 h UTC, solar zenith angle 52.9°, identified to be totally cloud covered. The random measurement error is negligible (∼ 0.1 %). Solid line is a model calculation using a standard nimbostratus cloud reaching from 6 to 7 km height (CTH) with optical thickness 5 (COT).

parison of both observations yields a mean CTH of about 7 km (±1 km). For comparison with modeled radiance, the GOME scene was assumed to be homogeneously cloud covered. In Fig. 3 the DOD around 393.37 nm for a cloud having a CTH of 7 km and a COT of 5 is compared with the observed DOD. The random measurement error is less than 0.1 % and therefore negligible. Excellent agreement is obtained.

Ring DODs calculated for sets of different COTs and CTHs are shown in Fig. 4. The Ring DOD derived from the GOME DOD using DOAS fitting is about 8.3 % of the radiance, which corresponds to a COT of ∼5 when assuming a CTH of 7 km (see Fig. 3). Other COT/CTH sets having the same Filling-in are indicated by a horizontal dashed line. It can be seen from Fig. 4 that Filling-in decreases with increasing CTH or increasing COT when observed from satellite. In this case clouds more or less shield part of the atmosphere in the UV/vis depending on their COT (a cloud with COT of more than ∼50 almost completely cuts off the atmosphere below its CTH). The resulting slant path of light decreases, implying a falling number of Rayleigh scattering events and their Raman-scattering contributions. Further decrease of Filling-in compared to the clear sky occurs due to enhanced Mie-scattered intensity for the same reason as for the ground-based case explained in the above section.

In case of large COT most of the observed light is reflected from the top layers of the cloud in satellite geometry. Changes of the Ring Effect due to clouds therefore depend more on CTH. Retrievals of CTHs are then possible using the known relation to Filling-in for COTs of more than ∼50 as shown in Fig. 4. This has already been demonstrated by *Joiner and Bhartia* [1995]. However, for smaller COT more light penetrates into the cloud and back, which has been accounted for in this study as it leads to significant changes of Filling-in. Otherwise the retrieval underestimates the CTH. As Fig. 4 shows also that several different combinations of physical atmospheric parameters in the model can fit the measurements, more information about COT and CTH is needed, e.g. using O_2-A absorption structures (see *Kurosu et al.* [1999]). First approaches to reproduce CTH/COT sensitive DOD observations by GOME at 393.37 nm (Ring), 477 nm (O_4), and 761 nm (O_2-A, including absolute optical depth modeling) simultaneously give best results for a 2-cloud-layer parameter set (CTH 3 and 7 km, COT 20 and 6). Further investigations are needed as vertically and horizontally high variabilities of real cloud scenes can occur. However, the potential of cloud retrieval schemes simultaneously using such measurements available from GOME and soon from SCIAMACHY and OMI, is promising.

3. Summary and Conclusions

For cases studied where reasonable knowledge of the local conditions exists, it was shown that SCIATRAN reproduces well the Ring Effect in cloudy atmospheres for both ground-based and satellite observations.

Filling-in is very sensitive to the presence of clouds in UV/visible measurements of scattered sunlight in zenith sky (ground) and nadir viewing geometry (satellite).

For the ground-based observations, both increases and decreases of Filling-in could be explained, which is a balance between the amount of Rayleigh- and Raman-scattering by air molecules and Mie-scattering at cloud and aerosol particles, both depending on COT.

For satellite nadir viewing in the UV/visible spectral range of backscattered solar radiation, it was shown that Filling-in is very sensitive to CTH, as well as COTs below ∼50. Retrievals of cloud parameters at such moderate COTs require suitable spectral information, e.g. from the O_2-A band. Further efforts are needed to investigate the potential to retrieve cloud parameters simultaneously from Ring-, O_4-, and O_2-A spectral structures and absolute op-

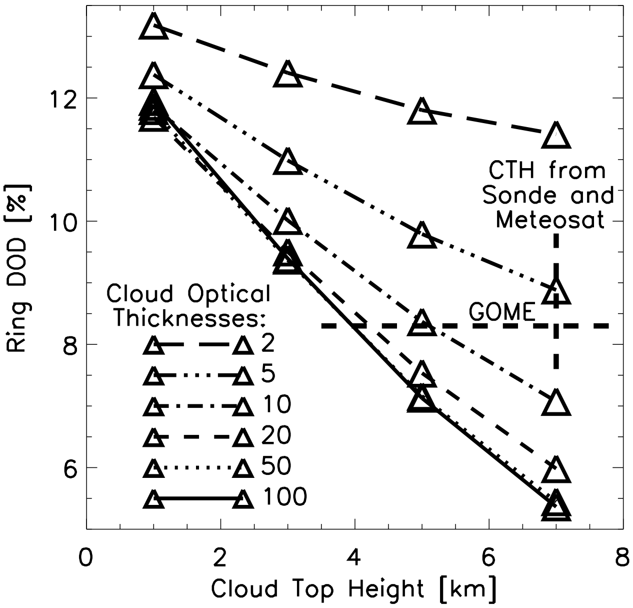

Figure 4. Ring DOD versus Cloud-Top Height (CTH) for clouds with different optical thicknesses as calculated with SCIATRAN for the Ca II Fraunhofer line Ring structure at 393.37 nm. The dashed vertical line indicates the cloud-top height as estimated using Meteosat (DWD, Germany) and balloon sonde temperatures (AWI, Germany), which are temporally and spatially near-coincident to the GOME measurement (see Fig. 3). The dashed horizontal line indicates CTH/COT combinations fitting the Ring DOD as calculated from the GOME measurement. A Ring DOD of 13.7 % is calculated for clear sky and a ground albedo of 5 %.

tical depth, e.g. as provided by GOME and SCIAMACHY, using radiative transfer models such as SCIATRAN. Also further statistically representative investigations are necessary to gain a more general picture of the Ring Effect in the presence of clouds.

Acknowledgments. We thank the Deutscher Wetterdienst, Germany, for making METEOSAT pictures available and the Alfred Wegener Institute for Polar and Marine Research for providing sonde temperature data. Part of this work was funded by the University of Bremen, the State Bremen, the German Space Agency, and the European Union. The IUP thanks ESA for funding and monitoring the Global Ozone Monitoring Experiment.

References

Burrows, J. P. et al., The Global Ozone Monitoring Experiment (GOME): Mission Concept and First Scientific Results, *J. Atmos. Sci., 56*, 151–171, 1999.

Grainger, J. F. and J. Ring, Anomalous Fraunhofer line profiles, *Nature, 193,* 762, 1962.

Joiner, J. and P. K. Bhartia, The determination of cloud pressures from rotational Raman scattering in satellite backscatter ultraviolet measurements, *J. Geophys. Res., 100(D11),* 23019–23026, 1995.

Kattawar, G. W. et al., Inelastic Scattering in Planetary Atmospheres, I, The Ring Effect, without Aerosols, *Astrophys. J., 243(3),* 1049–1057, 1981.

Kurosu, T. et al., Parameterization schemes for terrestrial water clouds in the radiative transfer model GOMETRAN, *J. Geophys. Res., 102(D18),* 21809–21823, 1997.

Kurosu, T. et al., CRAG – Cloud retrieval algorithm for the European Space Agency's Global Ozone Monitoring Experiment, *ESAMS Proceedings*, Vol. 2, 513–521, ESA, The Netherlands, 1999

Kurucz, L. R. et al., Solar flux atlas from 296 to 1300 nm, National Solar Observatory, Sunspot, New Mexico, *Technical Report,* 1984.

Platt, U. and D. Perner, Direct measurement of atmospheric HCHO, HNO_2, O_3, NO_2 and SO_2 by differential optical absorption spectroscopy, *J. Geophys. Res., 85,* 1980.

Richter, A., Absorptionsspektroskopische Messungen stratosphärischer Surengase über Bremen, 53° N, University of Bremen, Germany, Phd. thesis, Cuvillier Verlag, Göttingen, 1997.

Roscoe, K. K. et al., Slant column measurements of O3 and NO2 during the NDSC intercomparison of zenith-sky UV-visible spectrometers in June 1996, *J. Atmos. Chem., 32*, 281-314, 1999.

Rozanov, V. V. et al., GOMETRAN: A Radiative Transfer Model for the Satellite Project GOME, The Plane-Parallel Version, *J. Geophys. Res., 102(D14),* 16683–16695, 1997.

Shefov, N. N., Spectroscopic, Photoelectric, and Radar Investigations of Aurorae and the Nightglow, *Izd. Akad. Nauk, 1(25),* 1959.

Vountas, M. et al., Ring Effect: Impact of rotational Raman Scattering on Radiative Transfer in Earth's Atmosphere, *J. Quant. Spec. Rad. Transf., 60(6),* 943–961, 1998.

Winterrath, T. et al., Enhanced O_3 and NO_2 in Thunderstorm Clouds: Convection or Production?, *Geophys. Res. Lett., 26(9),* 1291, 1999.

R. de Beek, M. Vountas, V. V. Rozanov, A. Richter, and J. P. Burrows, Institute of Environmental Physics (IUP), University of Bremen FB1, P.O. Box 330440, 28334 Bremen, Germany. (e-mail: Ruediger.de_Beek@iup.physik.uni-bremen.de; Marco.Vountas@iup.physik.uni-bremen.de; Vladimir.Rozanov@iup.physik.uni-bremen.de; Andreas.Richter@iup.physik.uni-bremen.de; John.Burrows@iup.physik.uni-bremen.de)

(Received August 22, 2000; revised November 21, 2000;
accepted November 22, 2000.)