PROBING INTERNAL CLOUD PROPERTIES FROM SPACE

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ABSTRACT. We present model results and measurements indicating the possibility to derive information on cloud properties (e.g. the photon path lengths inside clouds) from satellite remote sensing instruments with moderate spectral resolution. Using novel satellite sensors providing (moderate) spectral information it is possible to analyse spectral absorption features as well as the strength of the Ring effect (Raman scattering on air molecules). These quantities depend in particular on internal cloud properties like average the photon path length. Thus they offer new information on cloud properties. From a first systematic investigation of GOME observations for October and November 1998 we found several examples of clearly enhanced O_2 and O_4 absorptions compared to clear skies, most of them were located at the edge of extended cloud patches. Our observations show that only if internal cloud properties are considered, the measured quantities can be understood.

1 INTRODUCTION

The measurement of cloud properties from space is usually performed by radiometers measuring the upwelling radiation at selected wavelengths providing images with high spatial resolution (1km or below). From such observations, information on the spatial distribution of clouds and - if the measurements are performed in the thermal IR - also on the cloud top height can be derived.
Since about one decade, novel satellite instruments were put in orbit which observe the backscattered sunlight from the earth in the UV/vis spectral range with moderate spectral resolution (≈0.2nm), but with coarse spatial resolution (GOME on ERS-2, SCIAMACHY on ENVISAT, OMI on AURA, see [1-3]. Such measurements offer completely new possibilities for the remote sensing of cloud properties. In addition to the observed absolute radiance, also narrow band spectral structures of atmospheric absorbers can be analysed. Especially from the observation of species with constant (and known) atmospheric concentration like the oxygen molecule O_2 or the oxygen dimer O_4, information on the atmospheric radiative transfer can be derived. From their measurements even information on the light paths inside the clouds can be obtained. In addition to the observation of atmospheric absorptions, also the spectral signature of Raman-scattering on air molecules (the so called filling-in of Fraunhofer lines or Ring effect [4]) can be measured with high precision. The strength of the Ring effect depends on the relative fraction of the observed photons, which have undergone Raman scattering events (besides inelastic scattering and reflection processes). Because clouds provide large amounts of additional scattering particles (for inelastic scattering), they strongly affect this relative fraction and therefore the strength of the Ring effect [5,6]. In our study we show that from these new set of cloud sensitive quantities, information on cloud properties, particularly on the light paths inside clouds can be obtained. First, we discuss the elementary cloud effects on these quantities and present results from radiative transfer modelling. Then we show exemplarily satellite measurements for the different effects of clouds and compare them to the model results.

1.1 Cloud influence on the O_4 and O_2 absorption

Clouds change the paths of the observed photons in two basic ways. First, clouds shield the atmospheric absorption below the cloud and thus reduce the absorptions compared to the clear sky case. In addition, multiple scattering inside the clouds can enhance the absorption path and thus increase the atmospheric absorption. Usually, for satellite observations the first effect is dominating the overall change and thus typically a decreased O_2 or O_4 absorption is observed when clouds are present. However, for a thick cloud at low altitude, the absorptions can be also enhanced compared to clear skies.
Two important aspects have to be considered:
a) Since O_2 and O_4 show different vertical profiles, clouds have different effects on the observation of both species.
b) O_4 absorption bands at various wavelengths can be measured, for which a cloud has different (relative) effects because of the different strength of Rayleigh-scattering.
Both facts can in principle yield additional information on of clouds. In Fig. 1, modelling results for O_2 and O_4 are presented. They are expressed as air mass factors, which describe the ratio of the measured slant column density (the trace gas distribution along the line of sight) and the vertical column density (the vertically integrated trace gas concentration):

$$AMF = SCD / VCD \quad (1)$$

The AMF describes the sensitivity of an observation with respect to the total atmospheric column.
For both species, enhanced AMF are found for thick clouds at low altitudes. For clouds at higher altitudes, the AMF decrease systematically. However, for the different species and wavelengths, a different dependence is found. It should be noted that the AMF for an altitude of zero indicate the clear sky cases for 5% ground albedo (lower values) or 80% ground albedo (higher values).

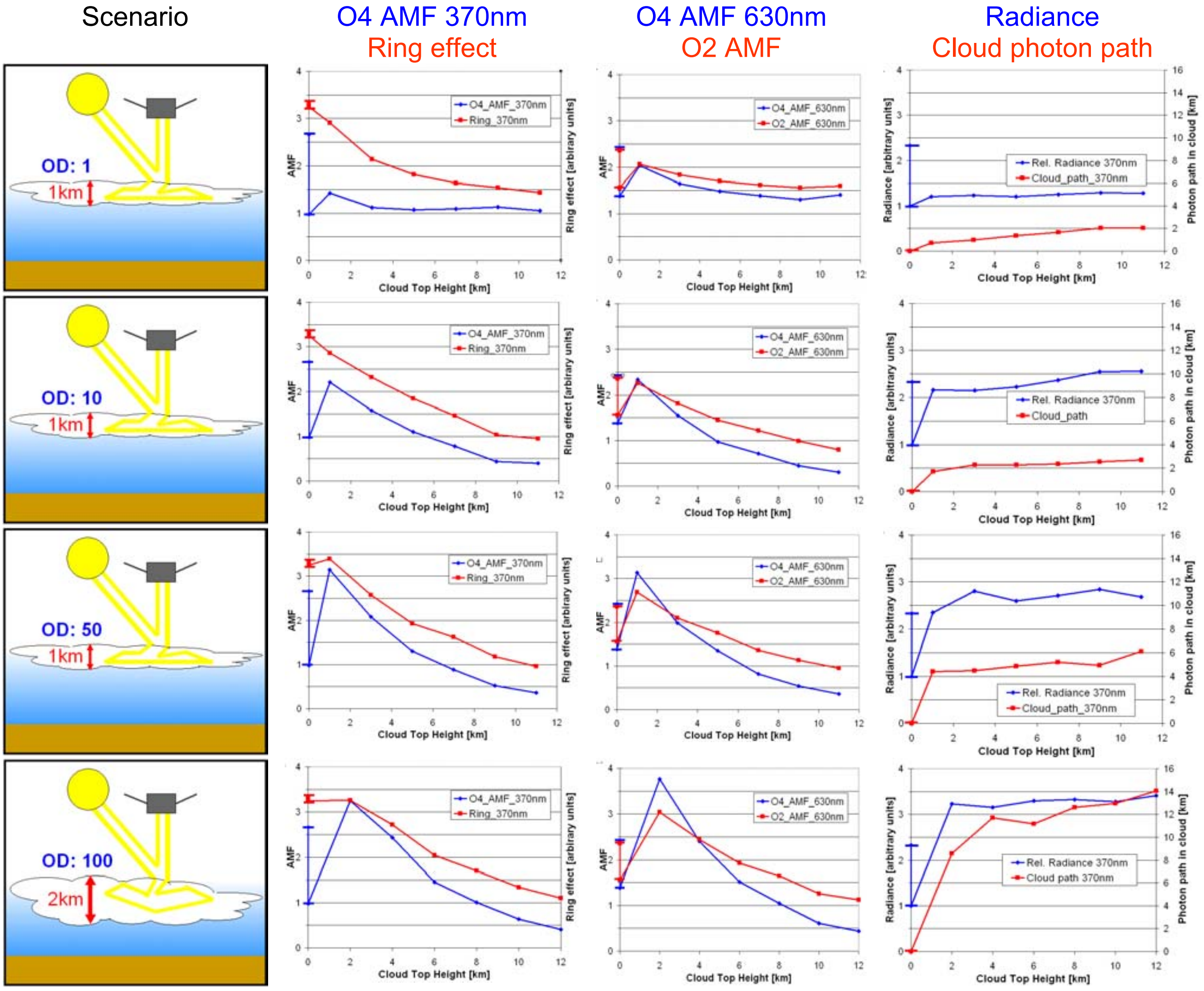

Fig. 1 Model results of the cloud influence on the observed O2 and O4 (expressed as AMF, see text), and on the Ring effect (left and center). In the right part, the corresponding (relative) radiance and the light path inside the cloud are shown. The results are obtained using the Monte-Carlo model TRACY [7]. For optically thick clouds at low altitude, enhanced O2 and O4 absorptions are found while the Ring effect is almost unchanged. For high clouds, the O2 and O4 absorptions and the Ring effect are systematically decreased. Please note that the values for an altitude of zero represent the clear sky cases for 5% ground albedo (lower values) or 80% ground albedo (higher values).

1.2 Cloud influence on the Ring effect

Clouds change the probability of a photon to be Raman-scattered in two ways: First, because of the additional particle scattering (inelastic scattering), the relative fraction of photons having experienced Raman-scattered is decreased. However, since the additionally received photons can have experienced long atmospheric light paths, their probability to be also Raman-scattered (in addition to be scattered on cloud particles) can also be increased. In total, low clouds hardly change the Ring effect compared to clear skies. However, with increasing altitude, the Ring effect can be strongly decreased making the observation of the Ring effect a good indicator of cloud top height [5].
In Fig. 1, modelling results for the Ring effect are presented. It should be noted that currently Raman-scattering is not implicitly included in our radiative transfer model TRACY [7] but is approximated by the modelled scattering processes and light paths. Therefore, the results are only expressed as relative units.

1.3 Cloud influence on the observed radiance

Clouds provide additional scattering centers in the atmosphere and therefore in almost all cases leads to an increase of the observed radiance. The highest increase of the radiance is measured over optically thick clouds.

1.4 Modelled Photon path lengths inside the clouds

In Fig. 1 also the modelled average photon paths for the different cloud scenarios are shown. Their magnitude depends especially on the assumed optical depth, with values of up to 14km for an optical depth of 100.

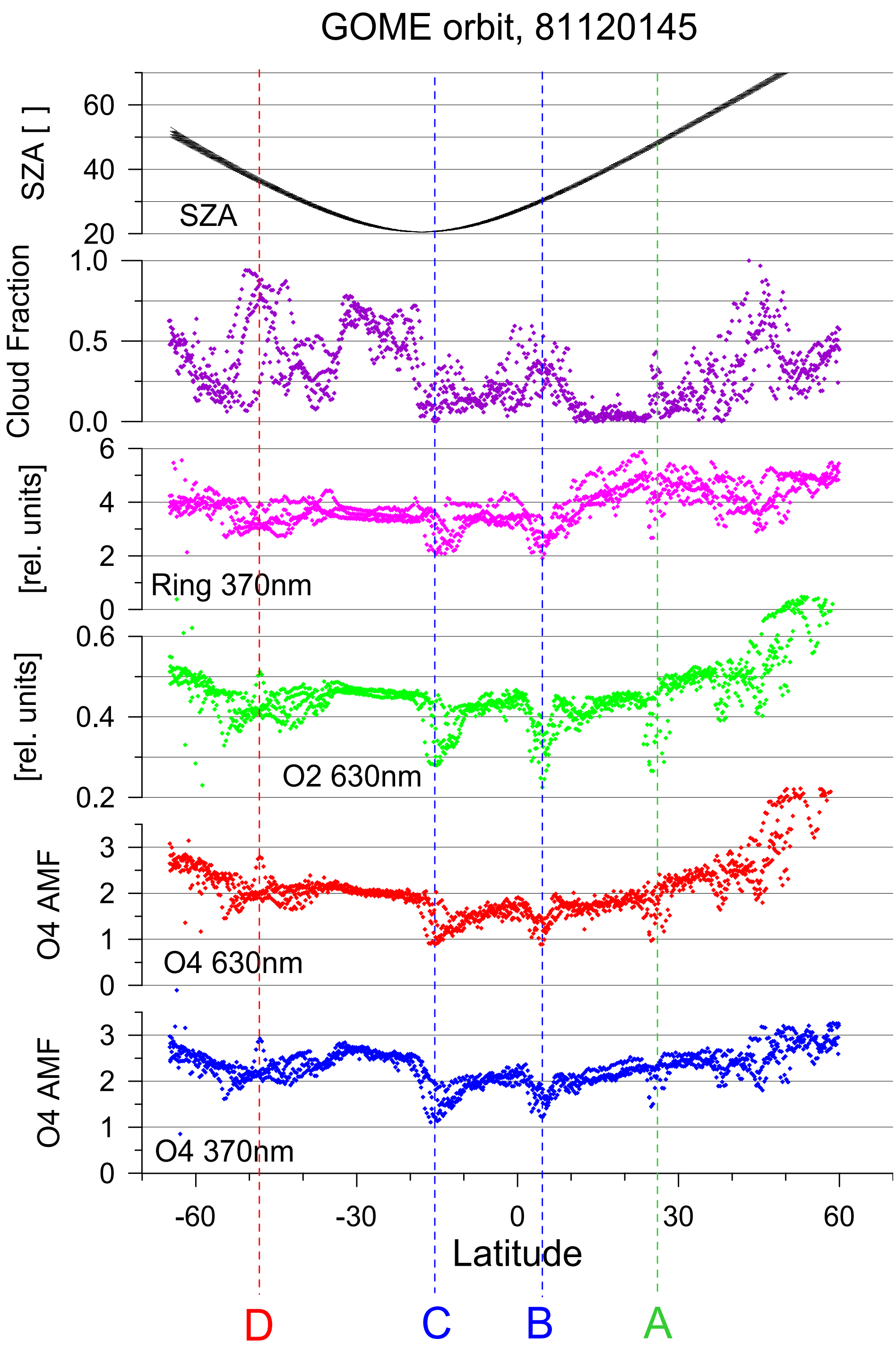

Fig. 2 Latitudinal cross sections of several quantities measured along one orbit of the GOME instrument on November, 20, 1998. For several cases (e.g. A,B,C) clouds lead to decreased values of the observed O2 and O4 absorptions and the Ring effect. For case D, multiple scattering inside a cloud increases the O2 and O4 absorption, while the Ring effect is almost unchanged (for details see text). The corresponding color-coded maps to these latitudinal cross sections are shown in Fig. 3.

2 OBSERVATIONS

In Figures 2 and 3, observations along one orbit of the GOME instrument on November, 20, 1998 are shown. Fig. 2 displays the latitudinal cross sections, while Fig. 3 shows the corresponding color-coded maps. In Fig. 3, also the cloud liquid water path derived from SSM/I observations is shown.

The different graphs present the variation of the cloud fraction, the Ring effect, the O_2 absorptions at 630nm and the O_4 absorptions at two wavelengths. It should be noted that the cloud fraction was analysed from the observed broad band intensity using the HICRU algorithm [8]. The measured O_2 absorptions haven't been converted into AMF due to the non-linearity caused by the strong and fine-structured O_2 absorption at 630nm which is not resolved by the GOME instrument.

Besides the overall influence of the solar zenith angle (top panel) causing the smooth variation with latitude, also several rapid changes of the measured quantities are found.

Four selected cases will be discussed in some detail below.

A) Typical case of the cloud influence on satellite observations: over the Atlantic, a medium or high cloud decreases the absorption of all species and also the strength of the Ring effect (shielding effect).

B and C) Similar to case A), but now the cloud effect combines with the similar effect of high mountain areas.

D) Case of increased O_2 and O_4 absorption, most probably caused by multiple scattering inside an optically thick cloud at low altitude. In contrast to the absorptions, the Ring effect stays almost unchanged. It might be important to note that similar increased O_2 and O_4 absorptions are often found at the edges of cloud patches.

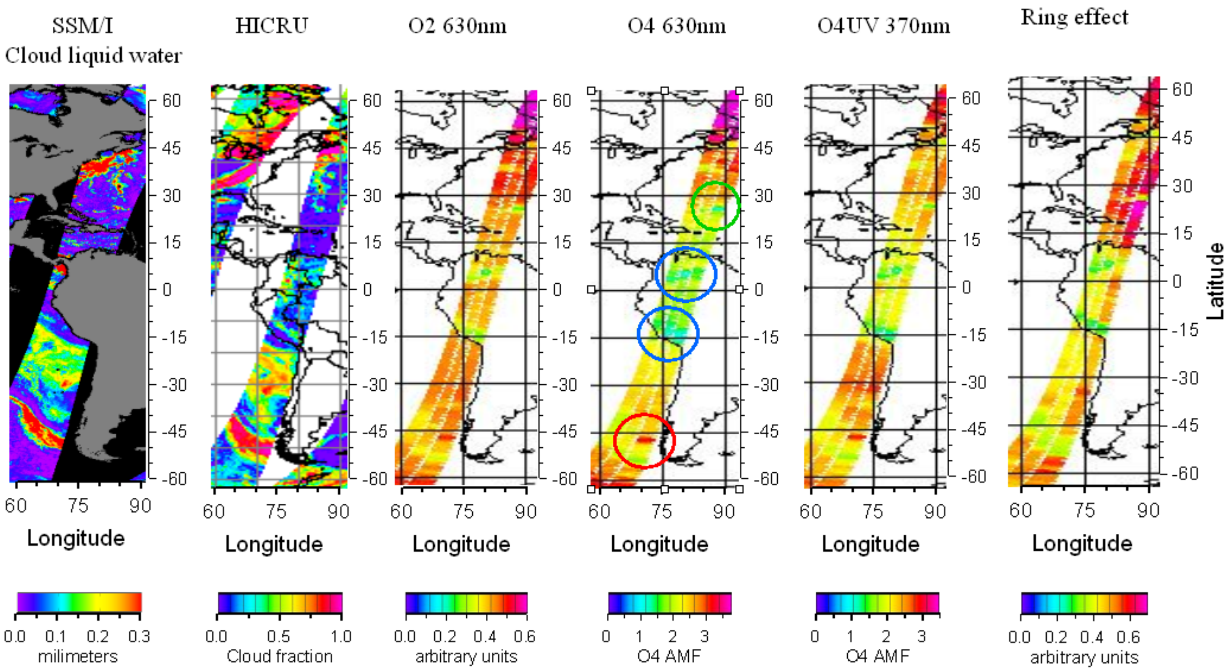

Fig. 3 Color-coded maps showing the spatial distributions of the results for the GOME orbit presented in Fig. 2. Also shown are observations of the cloud liquid water path observed by SSM/I. The locations of the case studies A,B,C,D (see text) are indicated by circles in the center graph. The area where the enhanced O2 and O4 absorptions are measured, are at the northern edge of an extended cloud patch.

3 CONCLUSIONS AND OUTLOOK

We present model results and measurements indicating the possibility to derive information on cloud properties (e.g. the photon path lengths inside clouds) from satellite remote sensing instruments with moderate spectral resolution.

From a first systematic investigation of GOME observations for October and November 1998 we found several examples of clearly enhanced O_2 and O_4 absorptions compared to clear skies, most of them were located at the edge of extended cloud patches. We found particular frequent cases for observations in the so-called narrow swath mode with pixel ground sizes of only 40x80km² (instead of 40x320km² for the standard observations). This indicates that for the large ground pixel sizes, local modifications of photon paths might compensate each other to a large degree. Our observations show that only if internal cloud properties are considered, the measured quantities can be understood. This finding indicates the potential of satellite observations with (moderate) spectral resolution to add new information on cloud properties. Future improvements should in particular address the following aspects:

a) realistic and quantitative radiative transfer modelling of the Ring effect and the absolute radiance

b) realistic radiative transfer modelling of 3D cloud structures
c) realistic radiative transfer modelling of the fine-structured O_2 absorption
d) consideration of the temperature dependence of the O_4 absorption
e) comparison with independent cloud information, e.g. from IR satellite instruments

Acknowledgements

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