GOME Satellite Detection of Ozone Vertical Columns over a Snow/Ice Covered Surface in the Presence of Broken Clouds

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1 Introduction

In the presence of broken clouds over snow or ice covered surfaces it is difficult for UV/VIS spaceborne sensors to distinguish between clouds and high reflecting surfaces. These uncertainties lead to problems in the ozone vertical column retrieval.

A new approach presented here characterizes the inhomogeneous pixel area (with broken clouds) by deriving an effective albedo and cloud-top-height. These parameters are determined by minimizing the difference between GOME measured sunnormalized radiances and corresponding model spectra in the spectral range of O_4 absorption near 370 nm. Extrapolation of this effective albedo to short wavelengths enables us to improve the ozone vertical column retrieval.

2 GOME ozone retrieval

The Global Ozone Monitoring Experiment GOME was launched aboard ESA's 2nd European Remote Sensing Satellite (ERS-2) in April 1995 into a polar sunsynchronous orbit. GOME measures radiances in the visible and ultraviolet spectral range (240 - 790 nm) in nadir viewing geometry.

The atmospheric parameters and their weighting functions are determined by the minimization of the differences between the GOME measured radiances R_{exp} and the model radiances R_{mod} calculated with the radiative transfer model GOMETRAN [6]:

$$||R_{exp}(\lambda, p_1, \ldots, p_N) - R_{mod}(\lambda, \tilde{p}_1, \ldots, \tilde{p}_N)||^2 \stackrel{!}{=} min. \quad (1)$$

Some of the parameters ($\tilde{p}_i, i = 1, \ldots, N$) included in this algorithm show very weak wavelength dependencies which can lead to high correlations with other atmospheric parameters. In order to avoid this, the contribution of parameters like the albedo, the rayleigh scattering coefficient, the aerosol scattering coefficient and the calibration function are described by an second order polynomial.

3 The modified inhomogeneous pixel approximation

If the field-of-view of the instrument is covered with broken clouds, the model radiance can be described in the inhomogeneous pixel approximation as follows:

$$R_{mod} = f_{cld} R^{cld}_{mod} + (1 - f_{cld}) R^{nocld}_{mod} \quad (2)$$

where R^{cld}_{mod} and R^{nocld}_{mod} are the model radiances with or without clouds respectively. The cloud fraction f_{cld}, which describes how much of the field-of-view is cloud covered is obtained from the PMD data, for example. The additional parameters taken into account for cloudy pixels are the cloud optical depth (τ_{cld}), the cloud-top-height (z_{top}) and the geometrical thickness of the cloud (Δz_{geo}).

If R_{mod} is written as

$$\begin{aligned} R_{mod} &= (1-f_{cld})R^{nocld}_{mod}(alb_{surf}, z_{surf}) + f_{cld}R^{cld}_{mod}(\tau_{cld}, z_{surf}) \\ &\quad + f_{cld}[R^{cld}_{mod}(\tau_{cld}, z_{top}) - R^{cld}_{mod}(\tau_{cld}, z_{surf})], \end{aligned} \tag{3}$$

the first two terms describe the inhomogeneous surface at ground height z_{surf}.

In this approach the cloud is regarded as an Lambertian surface with the albedo alb_{cld} and the inhomogeneous pixel area described by the first two terms is replaced by a homogeneous pixel with the effective albedo alb_{eff}:

$$R_{mod} = R_{mod}(alb_{eff}) + f_{cld}[R^{cld}_{mod}(\tau_{cld}, z_{eff}) - R^{cld}_{mod}(\tau_{cld}, z_{surf})]. \tag{4}$$

This is called the 'modified inhomogeneous pixel approximation' with the parameters alb_{eff} and z_{eff}, where z_{eff} is the 'effective' height of the Lambertian surface.

In the case of high reflecting surfaces the use of a 2nd order polynomial can lead to correlations in the ozone column retrieval if parameters like the cloud top height and the albedo are estimated in the same spectral range as the ozone vertical column.

In order to enhance the retrieval accuracy the atmospheric parameters are determined in three steps:

- Estimation of the effective cloud parameters alb_{eff} and z_{eff} in the spectral range from $355 - 385$ nm.
- Extrapolation of the effective albedo to shorter wavelengths.
- Retrieval of the ozone vertical column in the spectral range $320 - 340$ nm.

3.1 1. Step: Determination of z_{eff} and alb_{eff}

The influence of the atmospheric parameters p on the radiation can be described by the variations of the *'absolute optical depth'*(V_{AOD}) and the *'differential optical depth'*(V_{DOD}):

$$V_{AOD} = \ln R_{mod}(p+\Delta p) - \ln R_{mod}(p) \tag{5}$$

$$V_{DOD} = \{\ln R_{mod}(p+\Delta p) - \ln R_{mod}(p)\} - Pol \tag{6}$$

where Pol is a second order polynomial. While the variation of the absolute optical depth is defined by the change of the logarithm of the radiation, the variation of the differential optical depth shows the influence of the wavelength dependent parameters, i. e. the absorbing gases.

In the spectral range from 355 nm to 385 nm the only important absorption is from O_4 with a well known concentration profile. For a given cloud-top-height the effective albedo can therefore be determined by the minimization of the variations of the absolute and differential optical depth which results in two estimations for the effective albedo for a given cloud top height. The intersection of both curves delivers an unique solution to the effective albedo and cloud-top-height as shown in Fig. 1.

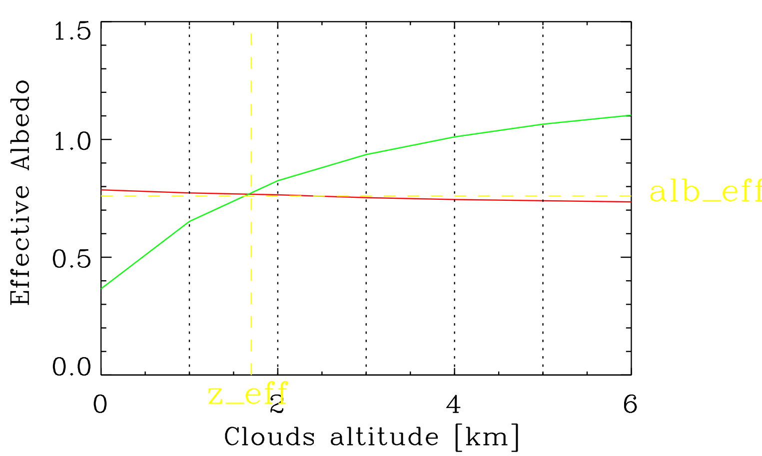

Fig. 1: Graphical determination of the effective albedo and cloud-top-height
The red line is the effective albedo by minimization of the absolute optical depth
while the green line results from the minimization of the differential optical depth

3.2 2. Step: Extrapolation of the effective albedo to shorter wavelengths

After the determination of the effective albedo in the spectral range of O_4 absorption an estimation of it for the spectral range of ozone absorption has t found. The minimization of the variations of the absolute optical depth (V_{AOD}) can be written as

$$||f(z_{eff}) - W_{alb}\Delta alb_{eff}||^2 \stackrel{!}{=} min \tag{7}$$

where $f(z_{eff})$ can be regarded as the difference between experimental and model spectra and W_{alb} is the albedo weighting function.

This leads to an estimation of the effective albedo in the spectral range from $355 - 385nm$:

$$alb_{eff}(\lambda) = \overline{alb}_{eff} + \frac{f(z_{eff}, \lambda)}{W_{alb}(\lambda)}. \tag{8}$$

An estimation of the effective albedo for the whole spectral range can now be given by a linear extrapolation of this function.

3.3 3. Step: Determination of the O_3 vertical column in the spectral window $320 - 340nm$

After the determination of the effective parameters and the extrapolation of the effective albedo to shorter wavelengths the ozone vertical column can be calculated by the minimization of the differences between GOME sun normalized radiances and the model data.

4 Retrieval results for simulated data for cloudy skies

In order to examine the accuracy of this method for the ozone column retrieval some calculations are made for simulated experimental data [3]. As an example some calculations are shown for different optical cloud depths (see Table 1 and Fig. 2).

Table 1: Data for simulated model calculations

cloud-top-height	3 km
cloud albedo	0.72
geom. thickness	2 km
sun zenith angle	30°
viewing geometry	nadir
cloud type	altostratus

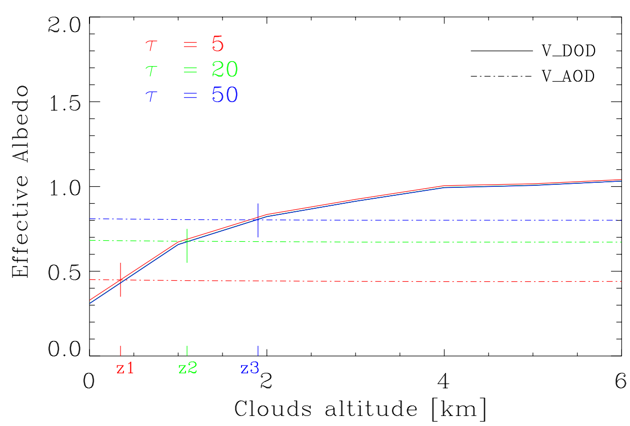

Fig. 2: Determination of the effective albedo and cloud-top-height for different optical cloud depths

This example shows that the *effective* cloud-top-height is lower than the real *physical* cloud-top-height we assumed in our simulation (cloud-top-height = 3km). This parameter shows a strong dependency on the optical depth of the cloud and reveals the lowest effective cloud-top-height for an optical depth of $\tau = 5$. This can be understood with regard to the cloud model used in this approach. In the retrieval clouds are regarded as Lambertian surfaces that are not pervious to solar radiation. This assumption can be made for clouds with high optical depths. In that case the effective cloud-top-height is close to the real cloud-top-height.

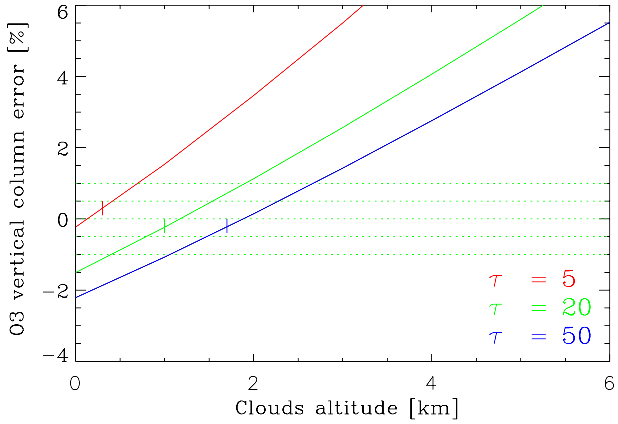

Fig. 3: Ozone vertical column error

The simulated data calculated for the same atmospheric scenario as before enables us to determine the ozone vertical column error.

For the different optical depths the ozone vertical column error with regard to the retrieval using the retrieval effective cloud-top-height is less than 0.5 %. The cloud albedo used to calculate the model data can be regarded as to be one possible reason for these deviations. This parameter does not exist for real clouds and is estimated here to be 0.72.

5 Retrieval results for experimental data

In the case of real experimental data the effective parameters show the same behaviour as in the simulated case. The derived effective albedo is not nessecarily identical with the physical cloud-top-height. As an example we calculated data for a high reflecting pixel in Greenland (Table 2):

latitude	70.73°
longitude	325.47°
sun zenith angle	84.8°
date	11.02.1999
UTC	14:42
orbit	90211144
pixelnumber	183
cloudfraction	1

Table 2: Geolocation data for Greenland pixel

The cloud fraction used in the calculations was obtained from the PMD-data [4].

The effective albedo determined by minimization of the variations of the differential optical depth has again a strong dependency on the cloud-top-height as shown in Fig. 4. This is explained by the influence of the absorbing gases on the differential optical depth.

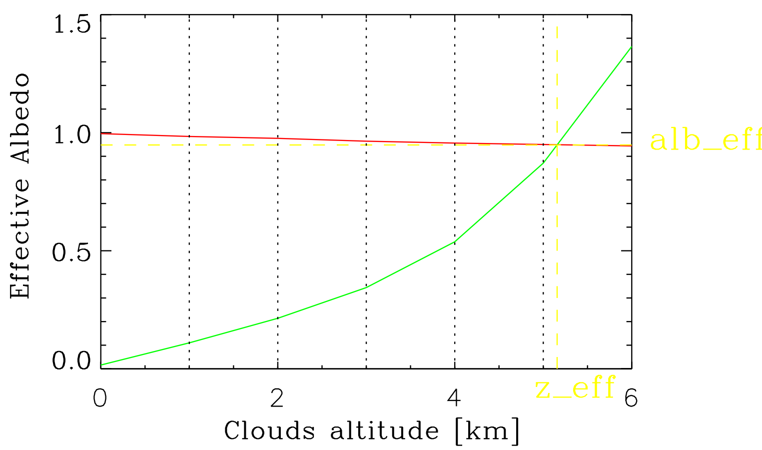

Fig. 4: Effective albedo and cloud-top-height for experimental data

In a next step the effective parameters determined in the spectral range of O_4 absorption can be used to examine the influence of the cloud-top-height on the ozone vertical column. As shown in Fig. 5 the ozone column shows a strong dependency on the cloud-top-height and can be estimated for the retrieved effective cloud-top-height.

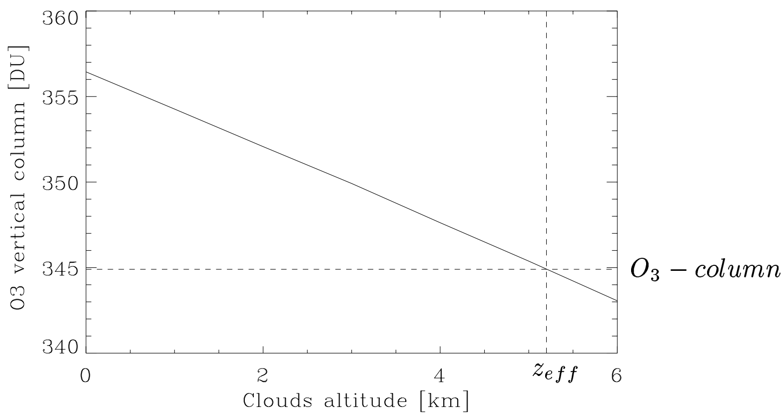

Fig. 5: Ozone column

For the effective cloud-top-height we graphically determined an ozone column of 344.9 DU. If we compare this value with the ozone column from the GDP-data, we can see that our ozone column is about 2.8% higher than the GDP-ozone column of 335.3DU altough our calculations consider only the ozone column above the Lambertian surface, i. e. above ~ 5 km. This deviation from the GDP-data shows qualitatively a similar behaviour as independent ozone column comparisons between GOME and SAOZ, which showed that the GDP underestimates ozone by $1\% - 11\%$ [5].

In order to examine the accuracy of this method the residual in the spectral range of ozone absorption can be compared with independent estimations of the residual. The residual can be regarded as the difference remaining between GOME data and model data due to calibration errors in the GOME data. These data are compared with independent data resulting from a comparison between GOME data and SBUV data [1]. The good agreement between both data sets shows that one possible reason for the remaining differences is the calibration error in the GOME data.

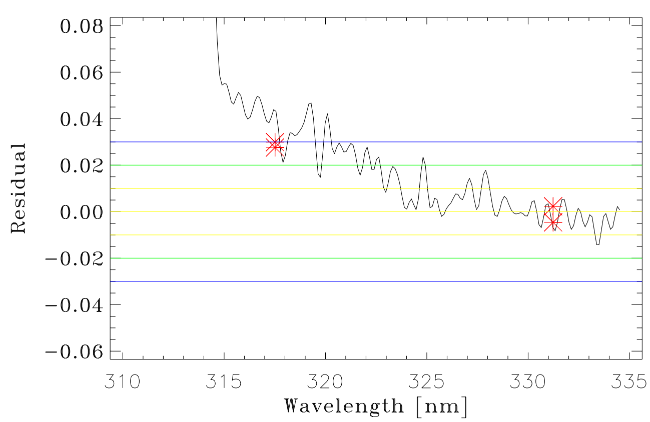

Fig. 6: Residual in comparison with independent data (red) [1]
Stars show the GOME - SBUV residuals.

6 Outlook

The good agreement between the calculated data and the independent data has been examined for only a few data up to now. This algorithm must be examined for more pixels and different scenarios in the near future and be validated in order to see if this promising approach represents an improvement in the accuracy of GOME ozone retrieval above high reflecting surfaces.

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