RETRIEVAL OF TOTAL WATER VAPOUR COLUMN AMOUNTS FROM GOME/ERS-2 DATA

S. Noël, M. Buchwitz, H. Bovensmann, J. P. Burrows

Institute of Environmental Physics, University of Bremen, FB 1, D–28334 Bremen, Germany

ABSTRACT

A method for the retrieval of vertical column amounts of atmospheric water vapour from measurements of the Global Ozone Monitoring Experiment (GOME) in the visible spectral region is presented. Originally developed for the determination of global ozone concentrations, the GOME instrument is operating successfully on ERS-2 since 1995, providing information also on several other atmospheric constituents like NO_2, BrO, OClO, H_2CO, SO_2, and recently also H_2O. The method for the derivation of water vapour amounts is based on the Differential Optical Absorption Spectroscopy (DOAS) approach, which has been extended to take into account effects arising from a strongly wavelength dependent absorption. Further improvements of the algorithm now allow to retrieve water vapour column densities under all cloud conditions. First results show an acceptable agreement between total water vapour columns derived from GOME measurements and H_2O columns obtained from the Special Sensor Microwave Imager SSM/I data, although the scatter of the GOME data is high, which needs to be further investigated.

INTRODUCTION

Water vapour is one of the most abundant minor atmospheric species. More than 99% of the water vapour is found in the troposphere where it significantly contributes to weather, atmospheric chemistry, and climate (IPCC, 1996). Its large spatial and temporal variability makes water vapour a tracer for tropospheric change and especially important for global models which aim to predict climate and global circulation models.

The main sources for water vapour data are currently in situ radio sonde measurements, space borne IR measurements, for example by the TIROS-N Operational Vertical Sounder (TOVS), and microwave soundings, for example with the Special Sensor Microwave Imager (SSM/I) (see e.g. Chaboureau et al., 1998, and references therein). Additionally, data of the Global Positioning System (GPS) have been used to determine atmospheric water vapour columns (see e.g. Rocken et al., 1997) in near real-time. Although reliable techniques to retrieve the total water vapour content over ocean exist, the information on global water vapour concentration over land are limited. More importantly, data about the vertical distribution of water vapour are missing, particularly for the upper troposphere and lower stratosphere.

Recently, two different approaches have shown that measurements of the Global Ozone Monitoring Experiment (GOME) may provide an additional source of global water vapour data (Noël et al., 1999; Maurellis et al., 2000).

The GOME instrument is a space-based grating spectrometer measuring both direct sunlight and sunlight, which is scattered by the Earth's atmosphere, in the spectral range between 240 and 800 nm. Measurements are performed in nadir viewing geometry with a spatial resolution of about 320 km × 40 km. GOME is operating successfully since 1995 on the ERS-2 satellite providing not only global distributions of O_3 and NO_2, but also column amounts of several other atmospheric constituents, for example BrO, OClO, SO_2, and HCHO (see Burrows et al., 1999, and references therein).

The current study presents an extension of the algorithm described by Noël et al. (1999) which now allows to retrieve water vapour total column amounts for cloudy scenes.

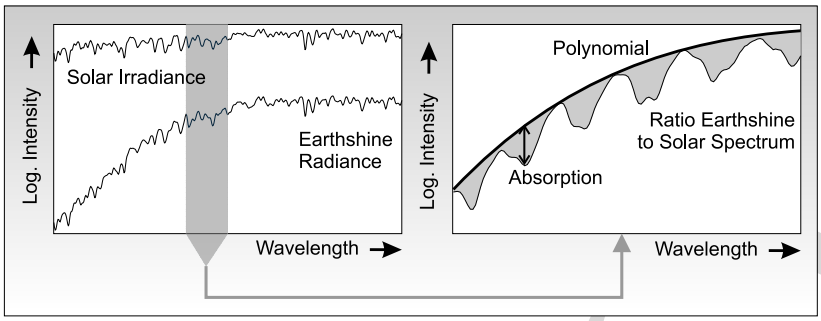

Fig. 1. Standard DOAS approach.

THE ALGORITHM

Standard DOAS

The algorithm to derive water vapour total column amounts from GOME data is based on the well-known Differential Optical Absorption Spectroscopy (DOAS) approach which has shown to be applicable to both ground-based and space borne measurements (see Burrows et al., 1999, and references therein).

The principle idea of DOAS is illustrated in Figure 1. The Earthshine radiance I is normalised to the solar irradiance I_0; then broadband contributions are separated from differential features by approximating the slowly varying components (Rayleigh- & Mie scattering, surface albedo) by a polynomial P. To the remaining differential absorption component reference cross sections σ are fitted. This results in the slant column density, which represents the absorber amount integrated along the (average) light path. A radiative transfer model is then used to compute a so-called air mass factor (AMF) m by which the slant column density is converted to the vertical column density C_V.

Assuming only one absorber in the spectral region needs to be considered, we find the following basic DOAS equation:

$$\ln\left(\frac{I}{I_0}\right) = P - \tau \tag{1}$$

with $\tau = \sigma\ m\ C_V$ being the slant optical depth.

Application to Water Vapour

Although the standard DOAS approach has been successfully used to retrieve the column amounts of various trace gases it is not directly applicable to the retrieval of water vapour for the following reasons:

Non-Linearity

One main assumption of standard DOAS is that the differential absorption depth is directly proportional to the amount of the absorber along the light path, i.e. the slant optical depth. This does not hold in the present case, where the strongly wavelength dependent absorption of water vapour is not resolved by the measuring instrument (GOME). As a consequence, the relation between differential absorption depth and absorber amount becomes non-linear. This is commonly referred to as saturation.

To solve this problem, the non-linearity has been parametrised in analogy to Halthore et al. (1997):

$$\tau = c\ C_V^b \tag{2}$$

where b describes the saturation effects, and c contains the (average) cross sections and the AMF. Both b and c depend on wavelength, spectral resolution, solar zenith angle (SZA), atmospheric conditions (pressure, temperature, clouds), and to some degree also on the shape of the water vapour profile. However, the parametrisation is such that – in analogy to Halthore et al. (1997) – b and c do not depend on the total vertical column density. The parameters b and c may be calculated from radiative transfer calculations (see Noël et al., 1999).

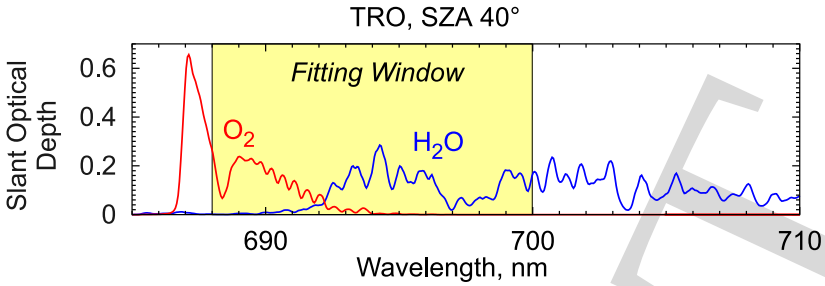

Fig. 2. Slant optical depth of O_2 and H_2O in the spectral region around the fitting window for a tropical background atmosphere and a solar zenith angle of 40°.

AMF Correction

An additional error source arises from the un-avoidable differences between the reference atmosphere used in the retrieval (i.e. the atmospheric conditions used in the determination of parameters b and c) retrieval and the real atmosphere. Because of these differences the computed AMF deviates from the 'real' value, which results in a wrong c parameter and thus in the end also in a wrong vertical column C_V.

This problem is solved by introducing an AMF correction factor which is determined using additional information from O_2 absorption features (see Noël et al., 1999, for details). The main idea is to assume that the AMF correction factors for O_2 and H_2O are the same; since the amount of O_2 is known, this factor may be determined for a given O_2 slant optical depth τ_{O_2}.

The above assumption of the same AMF correction factor in fact relies on several boundary conditions, namely that O_2 and H_2O absorption are of similar strength and occur in the same spectral region. This is assured by choosing the spectral window between 688 and 700 nm for the retrieval. In this wavelength range O_2 and H_2O absorptions partly overlap and the associated slant optical depths are of the same magnitude (see Figure 2).

Clouds

The algorithm as described up to here is identical with the algorithm used by Noël et al. (1999), where only cloud-free scenarios were considered. The present study extends the algorithm to cloudy scenes, which is essential because due to the large GOME ground pixels there are only very few measurements under cloud-free conditions (see also Koelemeijer and Stammes, 1999, in this context). The most common situation is a partly cloud-covered ground pixel.

The presence of clouds has a strong influence on radiative transfer. Clouds affect both the total intensity of the incoming light and the average light path, i.e. the AMF. In the completely cloudy case, no light in the spectral region considered here reaches the instrument from below the clouds.

A change in the absolute intensity is generally no problem for DOAS-like applications because all broad-band contributions are included in the polynomial P. The variation of the AMF is also (at least in first order) covered by the AMF correction factor, assuming that the change of the average light path due to the presence of clouds is similar for O_2 and water vapour. However, the shapes of the water vapour and O_2 profiles differ and thus the 'visible' amounts of water vapour and O_2 vary with cloud top height and cloud coverage. Therefore the actual values of the parameters b and c depend on cloudiness, and the coupling between water vapour and O_2 – and thus the AMF correction factor – is also a function of cloud top height and cloud coverage. This needs to be considered.

The solution for this problem is to introduce additional parameters for the 100% cloudy case and different cloud top heights. Partial cloud coverage is then handled by an appropriate combination of the cloud-free and completely cloudy case, assuming that the measured radiance for a cloudy ground pixel is the sum of the radiance of the cloud-free part and the radiance of the cloud covered part.

Modified DOAS Equation

The approach described above results in the following modified DOAS equation:

$$\ln\left(\frac{I}{I_0}\right) = P - a_1\left(\tau_{O_2} + c\ C_V^b\right) - a_2\left(\tau_c + c_c\ C_V^{b_c}\right) \quad (3)$$

In this equation, I and I_0 are the Earth and sun spectra measured by GOME.

Radiative transfer calculations using GOMETRAN (Rozanov et al., 1997; Buchwitz et al., 1998) provide the parameters b, c, and τ_{O_2} (for the cloud-free case) and the equivalent parameters b_c, c_c, and τ_c for 100% clouds. As noted before, these parameters depend on wavelength. To minimise the computational effort clouds have been modelled as reflecting layers with a lambertian albedo of 0.9 at the corresponding cloud top altitude. Comparisons with more complex cloud models have shown that this is sufficient for the present purpose. Pre-calculated parameter sets have been derived for a surface albedo of 5% (valid for ocean scenarios), eight cloud top heights (1 – 8 km), the six MODTRAN standard reference atmospheres (tropical, mid-latitude summer/winter, sub-arctic summer/winter, and 1976 US Standard atmosphere), and eight SZAs (0°, 20°, 40°, 50°, 60°, 70°, 80°). Parameter sets for other SZAs are derived by interpolation. Note that the algorithm implicitly includes the 'ghost column', i.e. the water vapour column below the clouds, in the determination of the parameters b and c for the cloudy case, assuming that the shape of the H2O profile does not change with the total column amount.

A non-linear fit applied to Eq. 3 results in the coefficients of the polynomial P, the scalar parameters a_1 and a_2, which contain the AMF correction and weights for cloud coverage, and finally the targeted vertical water vapour column amount C_V.

Note that even completely cloudy scenarios can be handled by this approach, although information from below the clouds is only taken from the reference atmosphere in this case.

Because most of the water vapour is located close to the surface, the resulting total columns for the cloudy case depend much on the cloud conditions and the chosen shape of the water vapour profile. This has to be considered in the interpretation of the results.

RESULTS

Application of the retrieval algorithm on simulated data (also derived from GOMETRAN calculations) have shown self-consistency. However, these simulations revealed that the choice of the appropriate parameter set is of crucial importance especially in the case of partial cloud coverage. The critical quantities in this context are cloud top height and reference atmosphere, which can not directly be derived from the geolocation and time of the GOME measurements.

There are several possibilities to determine cloud top height and the most appropriate reference atmosphere. Instead of using additional external information (e.g. climatologies or meteorological data) the present study prefers to get this information solely from GOME data using the O_2 absorption in the spectra and the cloud coverage from the GOME data product.

The simulations show that this approach succeeds in the determination of the cloud top height for a given cloud coverage, and also in the detection of the correct reference atmosphere. The mean deviation (for all cloud conditions) of the H_2O total column in the simulations is about 3%.

In a next step, the retrieval algorithm has been applied to real GOME measurements and compared with SSM/I daily gridded Integrated Water Vapor (IWV) data. These data are available over ocean only and have a spatial resolution of 0.5° × 0.5°. For the present analysis SSM/I data from the DMSP F-14 satellite measured on 14 June 98 during one descending orbit over the Atlantic ocean have been selected. This results in 318 coincidences between GOME and SSM/I. The SSM/I data have been averaged over the GOME ground pixels for the comparison.

The results of the comparison are displayed in Figures 3 and 4. As can be seen from Figure 3, the relative variation along the orbit is reproduced. There is also a general agreement of the absolute values of vertical columns, but the GOME results oscillate around the SSM/I values. At some regions, like in the tropics, this oscillation seems to be correlated in strength with the presence of clouds (illustrated by the GOME measured cloud coverage depicted in the lower part of Figure 3). However, there are also regions (especially in mid-latitudes) where despite of a high cloud coverage oscillations are small and the agreement between GOME and SSM/I data is good. In this context it has also to be considered that there is currently no

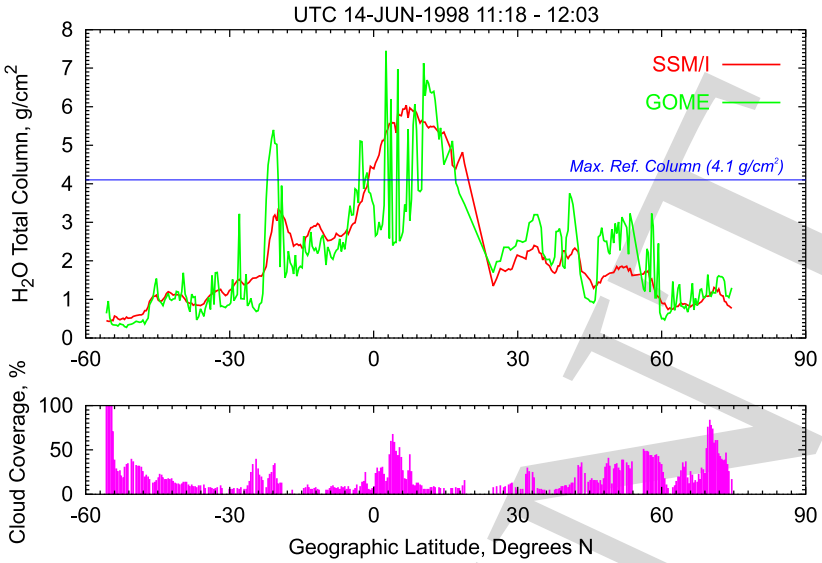

Fig. 3. Top: Variation of water vapour total columns along the selected orbit. Bottom: Associated cloud coverage taken from the GOME data product.

parameter set available which is representative for regions with very high water vapour concentrations. The maximum H_2O column density of the reference atmospheres used is 4.1 g/cm^2 whereas in the central tropics water vapour columns up to 6 g/cm^2 (and sometimes even more) are found. Therefore it is not possible to select an appropriate parameter set for these regions during the retrieval process, which results in large deviations between GOME and SSM/I results.

The large scatter and the typical underestimation of very large column densities can also be seen from Figure 4, where the GOME results are plotted versus the corresponding SSM/I data. Nevertheless, fitting a straight line to columns up to 4.1 g/cm^2 reveals an almost 1:1 correlation. This indicates that despite of the scatter, there are no systematic deviations between GOME and SSM/I.

A large scatter between GOME and SSM/I has also been observed by Noël et al. (1999) for almost cloud-free scenes and was mainly attributed to atmospheric variability, i.e. changes of the water vapour distribution between the time of the GOME and the SSM/I measurements. Insufficiently known cloud parameters place an additional uncertainty on the retrieved columns under cloudy conditions. It will be subject to future studies to further investigate the influence of the scatter on the quality of a possible GOME H_2O data product.

SUMMARY AND CONCLUSIONS

The method to retrieve vertical column amounts of water vapour from GOME data described by Noël et al. (1999) has been extended to handle cloudy scenes. Applications on simulated data show self-consistency. GOME water vapour columns retrieved with the described method show a general agreement with corresponding SSM/I values, but the scatter is high which is mainly attributed to short term atmospheric variations and insufficient knowledge of cloud parameters.

Future improvements of the retrieval method will include the addition of a reference atmosphere and associated parameter sets for extremely high water vapour content. An extension to higher ground albedos is also planned which will allow for the the retrieval of water vapour columns over land. Additional analysis of systematic effects, especially dependencies on the reference atmospheres, may result in a reduction of the observed scatter. For further studies also a more detailed assessment of retrieval errors is planned, especially with respect to the influence of errors in the cloud parameters. The possibility of deriving information about the vertical profile of water vapour will also be subject to further investigations.

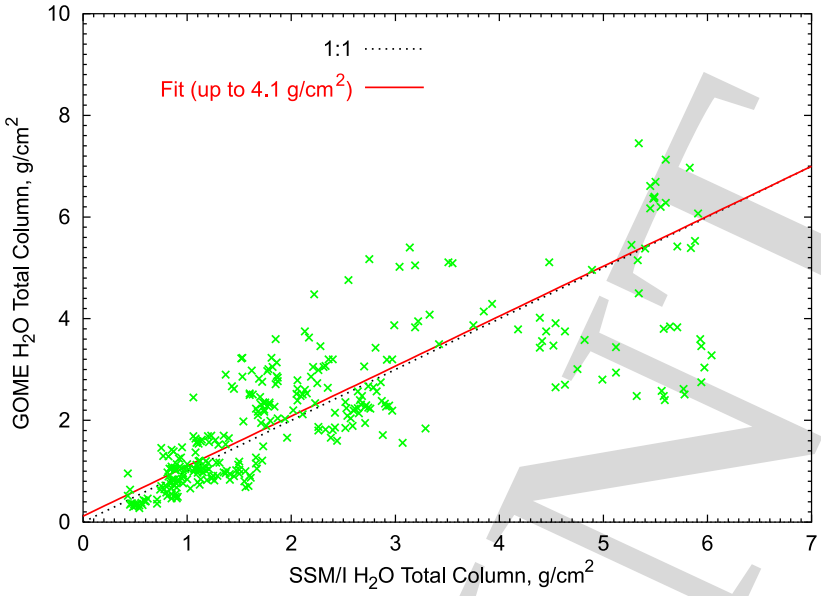

Fig. 4. Correlation between water vapour total columns derived from GOME and SSM/I measurements.

ACKNOWLEDGMENTS

SSM/I data have been provided by the Global Hydrology Resource Center (GHRC) at the Global Hydrology and Climate Center, Huntsville, Alabama. This work has been funded as part of the SCIAMACHY Scientific Support Study by the BMBF via GSF/PT–UKF under grant 07UFE12/8 and the by University of Bremen.

REFERENCES

Buchwitz, M., V. V. Rozanov, and J. P. Burrows, Development of a Correlated-k Distribution Band Model Scheme for the Radiative Transfer Program GOMETRAN / SCIATRAN for Retrieval of Atmospheric Constituents from SCIAMACHY/ENVISAT-1 Data, in Satellite Remote Sensing of Clouds and The Atmosphere III, volume 3495 of *Proc. SPIE*, pp. 171–186, 1998.

Burrows, J. P., M. Weber, M. Buchwitz, V. Rozanov, A. Ladstätter-Weißenmayer, et al., The Global Ozone Monitoring Experiment (GOME): Mission Concept and First Scientific Results, *J. Atmos. Sci.*, **56**, 151–175, 1999.

Chaboureau, J.-P., A. Chédin, and N. A. Scott, Remote Sensing of The Vertical Distribution of Atmospheric Water Vapor from the TOVS Observations. Method and Validation, *J. Geophys. Res.*, **103**, 8743–8752, 1998.

Halthore, R. N., T. F. Eck, B. N. Holben, and B. L. Markham, Sun Photometric Measurements of Atmopheric Water Vapor Column Abundance in the 940-nm Band, *J. Geophys. Res.*, **102**, 4343–4352, 1997.

IPCC, Climate Change 1995: The Science of Climate Change, Cambridge University Press, Cambridge, 1996.

Koelemeijer, R. B. A. and P. Stammes, Effects of clouds on ozone column retrieval from GOME UV measurements, *J. Geophys. Res.*, **104**, 8281–8294, 1999.

Maurellis, A. N., R. Lang, W. J. van der Zande, I. Aben, and W. Ubachs, Precipitable Water Vapor Column Retrieval from GOME Data, *Geophys. Res. Lett.*, **27**, 903–906, 2000.

Noël, S., M. Buchwitz, H. Bovensmann, R. Hoogen, and J. P. Burrows, Atmospheric Water Vapor Amounts Retrieved from GOME Satellite Data, *Geophys. Res. Lett.*, **26**, 1841–1844, 1999.

Rocken, C., T. V. Hove, and R. Ware, Near real-time GPS sensing of atmospheric water vapor, *Geophys. Res. Lett.*, **24**, 3221–3224, 1997.

Rozanov, V. V., D. Diebel, R. J. D. Spurr, and J. P. Burrows, GOMETRAN: A Radiative Transfer Model for the Satellite Project GOME – The Plane Parallel Version, *J. Geophys. Res.*, **102**, 16683–16695, 1997.