WATER VAPOUR RETRIEVAL FROM GOME DATA

INCLUDING CLOUDY SCENES

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INTRODUCTION

Water vapour is one of the most abundant atmospheric gases. More than 99% of water vapour is located in the troposphere where it significantly contributes to atmospheric chemistry, weather, and climate [1]. Its large spatial and temporal variability makes water vapour a tracer for tropospheric changes and especially important for global models which aim to predict climate.
The importance of water vapour has generated the need for global water vapour data. 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. [2], and references therein.
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 [3; 4].
The GOME instrument is a space-based grating spectrometer measuring both the extraterrestrial solar irradiance and the Earthshine radiance in the spectral range between 240 and 800 nm. A typical GOME spectrum is shown in Fig. 1. Measurements are performed in nadir viewing geometry with a spatial resolution of about 320 km $\times$ 40 km. GOME is operating successfully since 1995 from 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 [5], and references therein).
The current study presents an extension of the algorithm described by [3] which now allows for the retrieval of water vapour on a global scale.

THE ALGORITHM

The algorithm to derive water vapour total column amounts from GOME data is based on the well-known Differential Optical Absorption Spectroscopy (DOAS) approach (see Fig.2) which has shown to be applicable to both ground-based and space borne measurements (see [5], and references therein).
As in standard DOAS, the Earth-shine radiance is normalised to solar irradiance. All broadband contributions (like Rayleigh- and Mie scattering, surface albedo) are approximated by a polynomial, which is subtracted from the measured signal. The absorber amount is then derived from the remaining differential absorption structures, usually involving a radiative transfer model.
Although this kind of approach has been successfully used to retrieve the column amounts of various trace gases some modifications are required to make it applicable to the retrieval of water vapour from GOME data. These are explained in detail in [3] and will thus only be shortly addressed here.

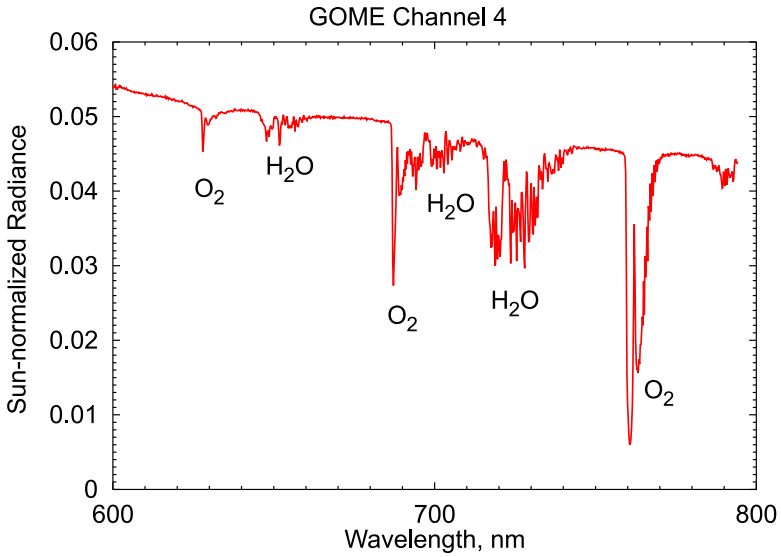

Fig. 1: Typical GOME Spectrum (ratio of Earthshine radiance to solar irradiance).

Non-Linearity

The main reason for the need of a modified approach is that the strongly wavelength dependent absorption of water vapour is not resolved by the GOME instrument because of its limited spectral resolution. This results in a non-linear relation between differential absorption and absorber amount. This non-linearity has been parametrised in analogy to [6]:

$$\tau = c\, C_V^b \tag{1}$$

where τ is the slant optical depth, C_V the water vapour vertical column, b describes the saturation effects, and c contains the (average) cross sections and the air mass factor (AMF), i.e. the factor which converts the slant column into a vertical column density. 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, it is a basic assumption that b and c do not depend on the total vertical column density. The parameters b and c may be calculated from radiative transfer calculations.

Air Mass Factor Correction

A common retrieval problem is that the reference atmosphere used in radiative transfer calculations usually differs from the real atmospheric conditions during the measurement. This results in an in-appropriate AMF, and as a consequence also in an wrong vertical column.

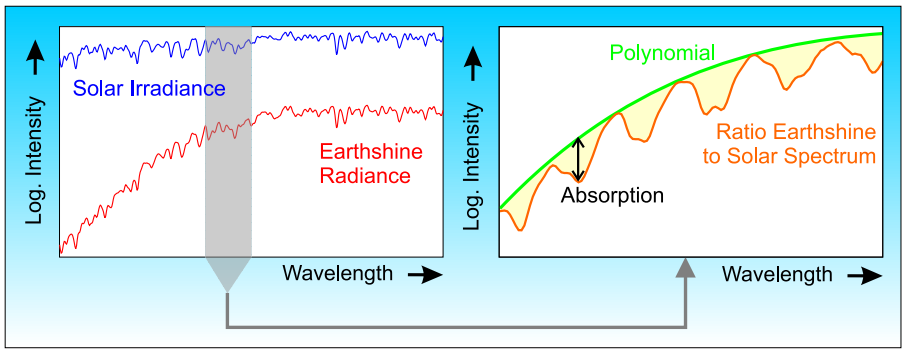

Fig. 2: The principal DOAS approach.

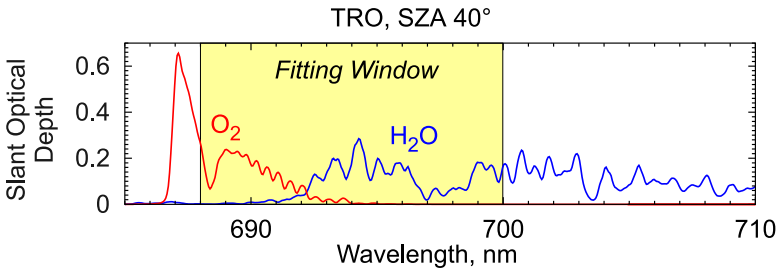

Fig. 3: Slant optical densities of O_2 and water vapour in the spectral region of the fitting window for a tropical reference atmosphere and a solar zenith angle (SZA) of 40°.

This problem is solved by introducing an AMF correction factor which is determined using additional information from O_2 absorption features. 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 Fig. 3).

Cloud Correction

Another problem of space-based measurements in the UV-VIS-NIR spectral region is that no information can be obtained from below clouds. For the retrieval of water vapour this is a serious issue, because most of the water vapour is located near the surface and thus not visible in the presence of clouds. Because of the large GOME ground pixels there are only very few measurements under cloud-free conditions. The most common situation is a partly cloud-covered scene. Therefore, clouds need to be considered in a retrieval algorithm which shall be applicable on a global scale.
Fortunately, some of the influences of clouds on the measured signal are already implicitly covered by the retrieval method described above. All broadband effects of clouds, i.e. increasing the total intensity of the incoming light, are included in the background polynomial. Changes in the AMF are – at least to some degree – covered by the AMF correction, 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 general problem remains that the GOME data do not contain information from below the clouds, and thus a large part of the water vapour column is invisible in the presence of clouds. Moreover, 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.
One solution of this problem is to compute additional parameters for different cloud top heights and cloud coverages. The appropriate parameter set is then selected using actual values for the cloud top height and coverage taken from the GOME level 2 data product.
A cloud correction algorithm which does less rely on given cloud top height and coverage is described in [7]. However, recent analysis results indicate that the algorithm described in the present paper is computationally faster and gives better results as long as the cloud parameters are sufficiently well known.

Modified DOAS Equation

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

$$\ln\left(\frac{I}{I_0}\right) = P - a\,\left(\tau_{O_2} + c\,C_V^b\right) \tag{2}$$

In this equation, I and I_0 are the Earthshine radiance and solar irradiance spectra measured by GOME.
Radiative transfer calculations using GOMETRAN [8; 9] provide the parameters b, c, and τ_{O_2}. As noted before, these parameters depend on wavelength, atmospheric conditions, and solar zenith angle.

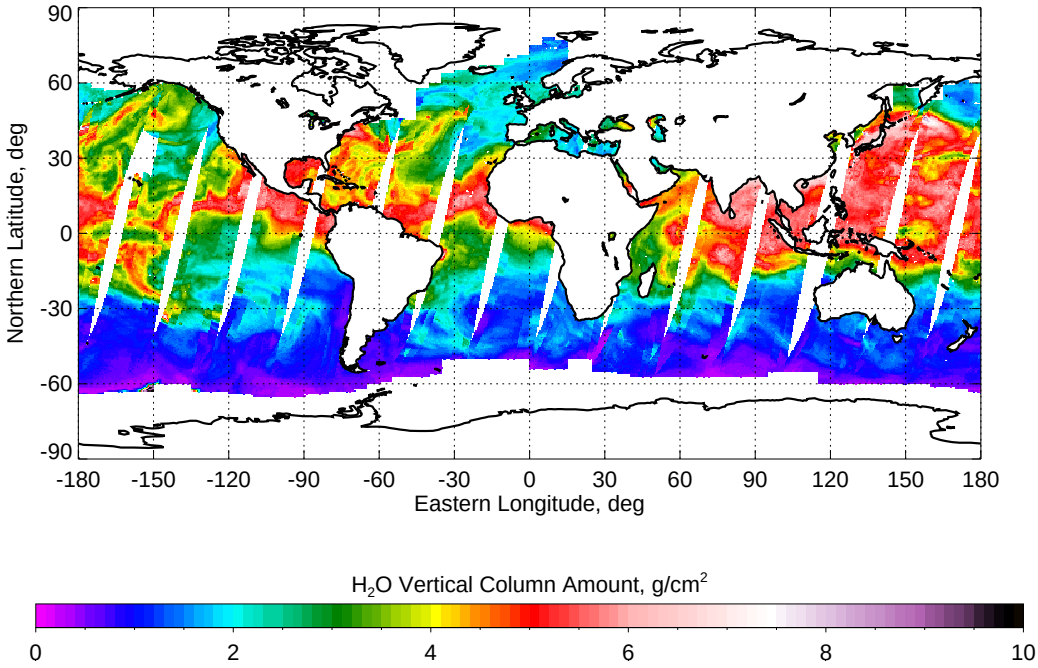

Fig. 4: Water vapour total column amounts measured by SSM/I on DMSP-F14 between 1 August 2000 and 3 August 2000 (descending orbits).

To minimise computational efforts clouds have been modelled as reflecting layers of lambertian albedo 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 parameters sets have been derived for a surface albedo of 5% (valid for ocean scenarios), eight cloud top heights (1 – 8 km), cloud coverages of 0%, 20%, 40%, 60%, 80%, and 100%, 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 and cloud conditions are derived from interpolation.
A non-linear fit applied to equation (2) results in the coefficients of the polynomial P, the AMF correction factor a, 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.

RESULTS

To judge upon the quality of the retrieval, GOME water vapour columns are 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 between 1 and 3 August 2000 during descending orbits have been selected. A composite image of these date is shown in Fig. 4.
The corresponding GOME water vapour data have been derived from radiance and irradiance spectra extracted from GOME level 1 data and cloud coverage and cloud top height values taken from GOME level 2 data for the same three days. The retrieval has been successfully performed for all GOME subpixels. For the comparison with SSM/I backscan pixels have been omitted in the plots, and the GOME data have been gridded to 0.5° × 0.5°.

Two different types of retrieval have been performed:
At first, a simple approach has been used which assumes for all measurements a cloudfree scenario and always uses the tropical reference atmosphere. In this case, all atmospheric variations and different cloud conditions have to be handled by the AMF correction.
The second approach uses the full capabilities of the retrieval model: Parameter sets are determined for the actual cloud conditions, and an automatic selection of an appropriate reference atmosphere is performed by an additional analysis of

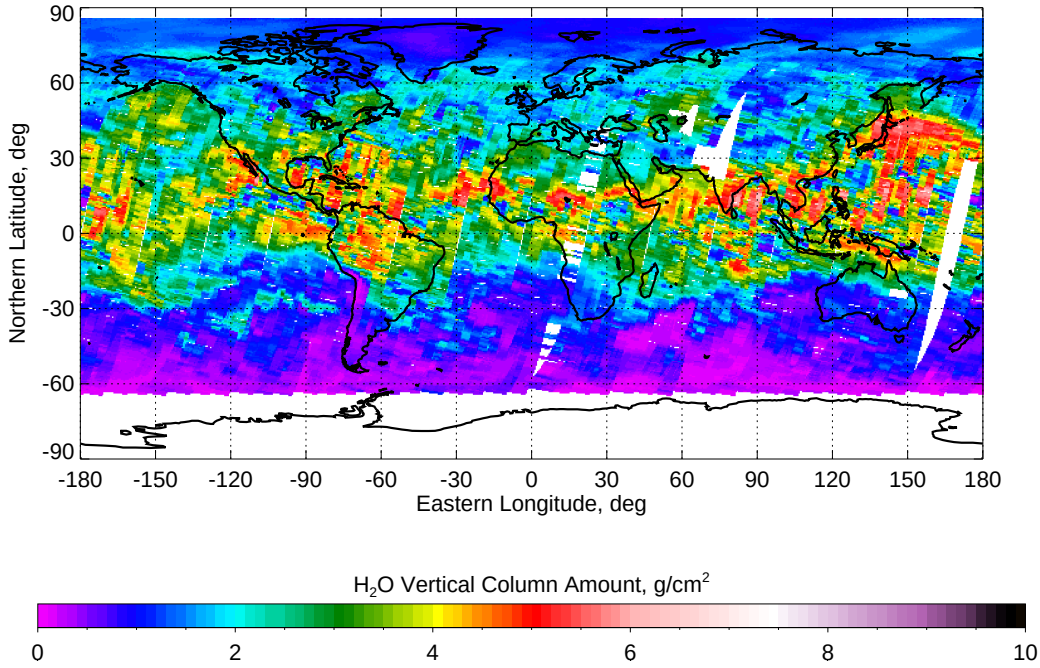

Fig. 5: Water vapour total column amounts determined from GOME measurements between 1 August 2000 and 3 August 2000. No specific cloud correction is performed, and a tropical reference atmosphere is used.

O_2 absorption features.

As can bee seen from Fig. 5, even the simple model is quite successful on a global scale. The general structures and magnitudes of the water vapour distribution seen in the SSM/I data are reproduced. Moreover, in contrast to SSM/I, the retrieval also produces consistent results over land. However, in some regions, like in the eastern part of the Pacific ocean, the retrieved GOME columns are much lower than the SSM/I values.

In these cases the AMF correction fails because the background atmosphere used in the parameter calculation is too far away from the real atmospheric conditions, mainly due to the presence of clouds. In fact, these problem areas may be clearly identified by a low AMF correction factor. This is illustrated in Fig. 6, where all data have been omitted for which the retrieval results in an AMF correction factor smaller than 0.8. Obviously, all areas which showed too low columns in Fig. 5 are now removed in Fig. 6.

Running the 'full' model – including cloud correction – results in the total water vapour columns displayed in Fig. 7. As can be seen, the retrieval still works for non-cloudy scenes. For cloudy scenes the retrieved columns are higher than without cloud correction, and the agreement with SSM/I data is much better. However, in some cloudy regions the water vapour columns are significantly overestimated, and in general the scatter of the data is much larger in the presence of clouds.

There are several possible reasons for these remaining problems: First of all, the quality of the retrieval strongly depends on a good knowledge of cloud top height and cloud coverage. The cloud top height given in the GOME data product is taken from a climatology and thus may not match reality. The other critical point is that because no information from below the clouds can be derived from the GOME data, the total column for a cloudy scene depends on the choice of the reference atmosphere of which only six different types are currently in use. Therefore it is concluded that the retrieval works also for cloudy scenes, but in these cases additional errors are introduced resulting from the smaller information content of the measurement data.

Summary

A method to retrieve vertical column amounts of water vapour from GOME data has been presented. This method is based on a modified DOAS approach and especially considers the influence of saturation, incorrect AMFs, and clouds. It has been shown that the retrieval of water vapour columns from GOME data is possible on a global scale, and especially that GOME water vapour columns can also be retrieved over land. Comparisons between GOME and SSM/I water vapour

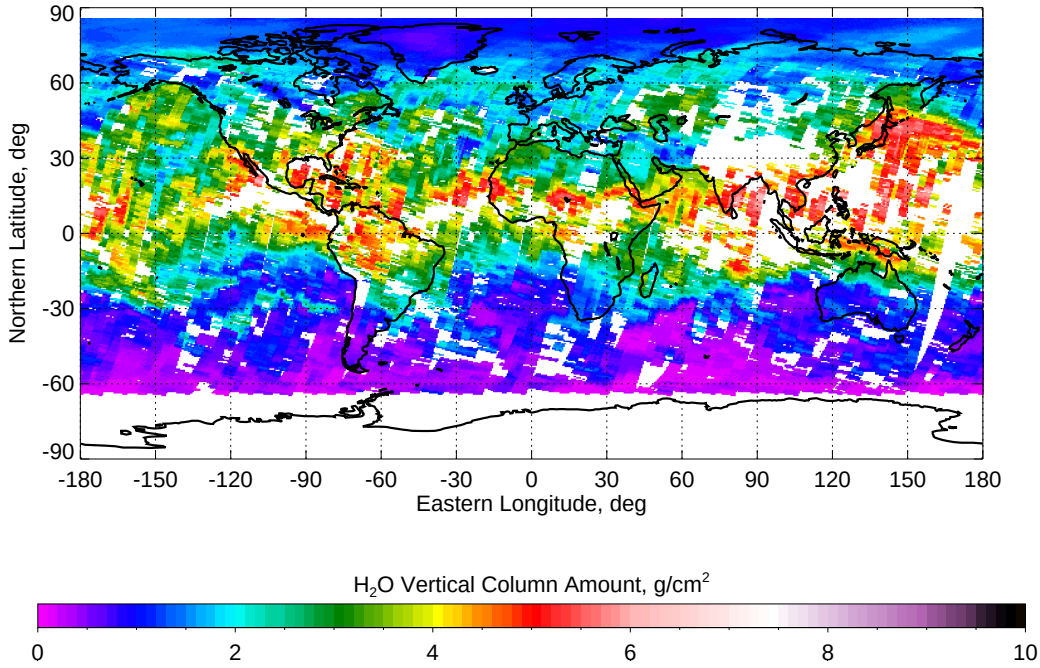

Fig. 6: Same data as in Fig. 5, but only data with AMF correction factors larger than 0.8 are displayed.

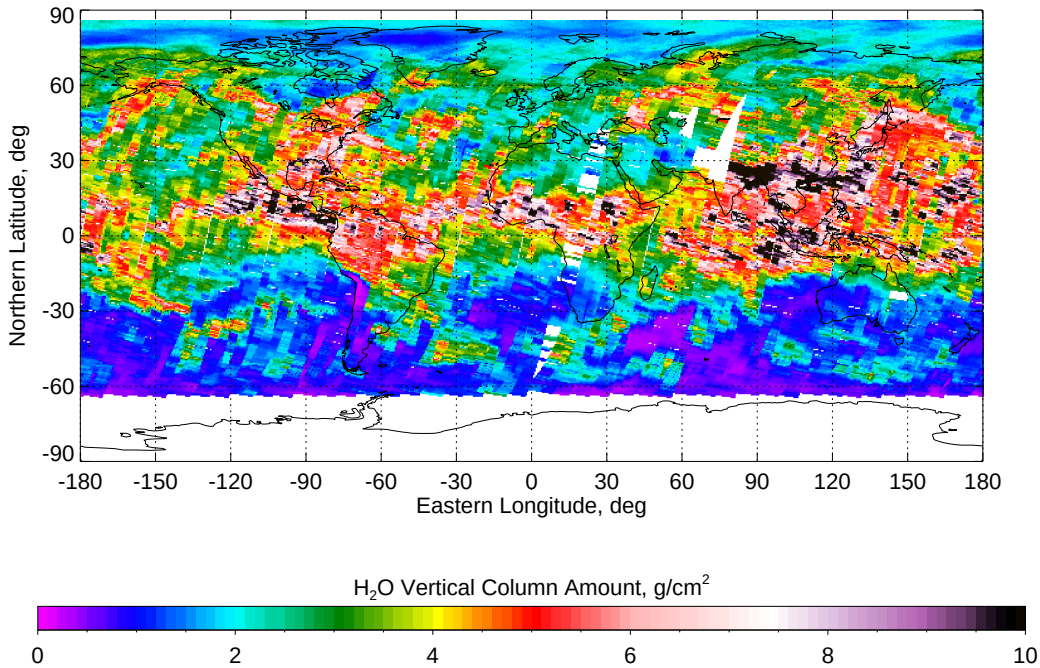

Fig. 7: Water vapour total column amounts determined from GOME measurements between 1 August 2000 and 3 August 2000. The retrieval includes an automatic determination of the reference atmosphere and additional cloud correction.

columns show a good general agreement, even if no explicit cloud correction is performed. Areas where the cloudfree approach fails may be clearly identified. Improvements are achieved with an additional cloud correction, but the results are very sensitive to the choice of the reference atmosphere and the cloud top height and cloud coverage used.
Future studies shall look into other sources of (better) cloud parameters, other cloud correction algorithms, or a better climatology. The possibility of deriving information about the vertical profile of water vapour will also be subject to

further investigations.

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