Global trends of water vapor and cloud cover (1996-2002) observed by the satellite instrument GOME on ERS-2

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Summary. Global data sets of the total water vapor column ad cloud cover are analysed from GOME measurements in the red spectral region. In contrast to other satellite observations of H_2O the UV/vis observations have the advantage to be of similar sensitivity over both land and ocean. In addition, they are sensitive in particular for the surface near layers where most of the H_2O column is located. Information on the atmospheric cloud cover was derived from the observed broad band intensity as well as the oxygen (O_2) absorption. While the first quantity is mainly a measure of geometrical cloud fraction, the latter also yields information on the cloud altitude. The spatial trend patterns (1996-2002) of the H_2O and cloud cover show both positive and negative signs. Especially over the southern hemispheric oceans very similar trend patterns are found which also well agree with those of the surface temperature. In contrast, in the northern hemisphere, especially over the continents the trend patterns are much less correlated and even opposite trends for H_2O and the surface temperatures are found. The trend patterns in the tropics are similar to those of the anomalies during the ENSO phenomenon 1997/98. Especially the positive trend over the central Pacific coincides with strong positive ENSO anomalies over the same region.

Introduction

Atmospheric water vapor is the most important greenhouse gas contributing about 2/3 of the natural greenhouse effect. In contrast to other greenhouse gases like CO_2 and CH_4 it has a much higher temporal and spatial variability. The correct understanding and assessment of atmospheric water vapor with respect to the earth's energy budget is further complicated by its role in cloud formation and transport of latent heat. Today, many details of how the hydrological cycle reacts to climate change (water vapor feedback) are still not understood. Especially for the tropics, which contribute strongest to the water vapor greenhouse effect, the strength of the water vapor feedback is under intense debate [Held and Soden, 2000 and references therein; Minschwaner and Dessler, 2004]. Here we present global data sets of total column precipitable water and cloud cover for the period 1996-2002. We investigate the temporal and spatial patterns and relate them to surface near temperatures.

GOME on ERS-2

The GOME instrument is one of several instruments aboard the European research satellite ERS-2 [European Space Agency (ESA), 1995; Burrows et al., 1999]. It consists of a set of four spectrometers that simultaneously measure sunlight scattered and reflected from the Earth's atmosphere and ground in total of 4096 spectral channels covering the wavelength range between 240 and 790 nm with moderate spectral resolutions. The satellite operates in a nearly polar, sun-synchronous orbit at an altitude of 780 km with an equator crossing time at approximately 10:30 local time. While the satellite orbits the earth in an almost north-south direction, the GOME instrument scans the surface of earth in the perpendicular east-west direction. During one scan, three individual ground pixels are observed, each covering an

area of 320 km east to west by 40 km north to south. They lie side by side: a western, a center, and an eastern pixel. The Earth's surface is totally covered within 3 days (poleward from about 70° latitude within 1 day).

Data analysis

In this study, from GOME data we analyse three products: The total column precipitable water, and two cloud related quantities. One cloud product (HICRU, for details see below) is based on broad spectral measurements with a high spatial resolution. The water vapor product and the second cloud product are based on Differential Optical Absorption Spectroscopy (DOAS) performed in the wavelength interval 611-673 nm of the measured GOME spectra. Besides the H_2O absorption, also the cross sections of molecular O_2 and the oxygen dimer O_4 are taken into account. From the DOAS analysis, the slant column densities (SCD, the concentration integrated along the light path) of these species are derived. In the second step the SCDs are converted in more suitable quantities: the vertical column density of water vapor (also referred to as total column precipitable water) and cloud properties (see below). One specific advantage of the DOAS method is that it is sensitive to relative (differential) absorptions; thus our results are almost independent on instrument degradation.

H_2O analysis

Several algorithms for the retrieval of the total column precipitable water (usually referred to in DOAS literature as vertical column density, VCD) in the red part of the spectrum from GOME were developed in recent years [Casadio et al., 2000; Noël et al., 2002; Maurellis et al., 2000; Lang et al., 2004; Lang, 2003 and references therein]. In contrast to these other methods, our water vapor algorithm is directly based on the results of the spectral analysis using Differential Optical Absorption Spectroscopy (DOAS [Platt, 1994]) and does not include explicit numerical modeling of the atmospheric radiative transfer.
In this study we utilize the measured O_2 absorption (instead of the absorption of the oxygen dimer O_4) for the correction of atmospheric radiative transfer modifications, e.g. due to clouds [Wagner et al., 2005a,b]. Compared to the O_4 absorption, it can be analyzed with substantially higher precision, which is of paramount importance for trend studies.
The desired total column precipitable water (TCPW) is the vertically integrated water vapor concentration. It is calculated as follows:

$$TCPW = VCD_{H_2O} = \frac{SCD_{H_2O}}{SCD_{O_2} / VCD_{O_2}} = \frac{SCD_{H_2O}}{AMF_{O_2}} \qquad (1)$$

Here SCD_{H2O} and SCD_{O2} are the measured slant column densities of water vapor and O_2, respectively. The VCD_{O2} is calculated from an average atmospheric pressure profile. The ratio of the SCD_{O2} and VCD_{O2} defines the 'measured' air mass factor (AMF_{O2}) [Solomon et al., 1987; Marquard et al., 2000; Wagner et al., 2003], which is used for the conversion of the measured SCD_{H2O} into the desired total column precipitable water (VCD_{H2O}). Our simple approach has the advantage that it corrects for the effects of varying albedo, aerosol load and cloud cover without the use of additional independent information (which is usually not available). Although the effects of clouds on the measured total column precipitable water are basically corrected by the application of the measured air mass factor, due to the different altitude profiles of H_2O and O_2, systematic cloud effects still appear [Wagner et al., 2003; 2005a,b]. Thus, for the trend analysis only mainly cloud free observations (the O_2 absorption is between 80% and 95% of the maximum O_2 absorption were used. For DOAS studies, the

term vertical column density (VCD) expressed in molecules per cm² is more commonly used. However, in the existing meteorological literature it is usually referred to as total column precipitable water and is expressed in units of g/cm².

Cloud analysis

Information on cloud properties can be derived from GOME observations in various ways [Kuze and Chance, 1994; ESA, 2000 and references therein, Koelemeijer et al., 2001, Wagner et al., 2003; 2005a]. In this study we investigate two cloud sensitive quantities. The Heidelberg Iterative Cloud Retrieval Utilities algorithm (HICRU, see Grzegorski et al. [2004] and Wagner et al. [2005a]) is based on the observed broad band intensity from the so called PMD sensors, which have a much higher spatial resolution (20 x 40 km²) compared to the standard GOME ground pixel [ESA, 1995]. The HICRU cloud algorithm yields an 'effective' cloud cover, which is a measure of cloud fraction and cloud brightness (mostly independent of the cloud height). For more details please refer to Grzegorski et al., [2004]. It is important to bear in mind the limitations of the HICRU algorithm (like all intensity based cloud algorithms in the visible spectral range) in correctly quantifying the cloud fraction over ice and snow covered surfaces. Over surfaces free of snow and ice the uncertainty of the HICRU cloud fraction is <10% [Grzegorski, 2003; Grzegorski et al., 2004].
The second cloud product is based on the observed O_2 absorption. If clouds appear they shield (part of) the atmospheric O_2 column; thus a reduced O_2 absorption (compared to the clear sky absorption) is a measure for the shielding of the lower atmospheric layers by clouds. However, the measured O_2 absorption depends on both cloud fraction and/or cloud top height: a measurement over a high cloud fraction and low cloud altitude might yield the same result as a measurement over small cloud fraction and high cloud altitude.
Our O_2-cloud product is simply the (negative) observed O_2 SCD divided by the maximum O_2 SCD. We will refer to the O_2 cloud product as 'cloud shielding' in the following.

$$Cloud\ shielding = -VCD_{O_2} = -\frac{SCD_{O_2}}{SCD_{O_2}\ \max} \qquad (2)$$

As for the HICRU cloud cover, also the O_2 cloud cover is affected by the surface albedo (but by a smaller amount). The uncertainty of the analyzed O_2 absorption is very small; from the residual structure of the spectral analysis we estimate the uncertainty to be <2%.

Results

In Fig. 1 the global trend patterns of the total column precipitable water and of both cloud products are compared to those for the surface temperature. The temperatures data are taken from the Goddard Institute for Space Studies (GISS), see http://www.giss.nasa.gov/data/update/gistemp/. They are derived from station measurements of the air temperature for land, and satellite observations of night-time sea surface temperatures over the oceans, see Hansen et al. [2001] and Reynolds et al. [2002].
Over large parts of the globe the H_2O VCD and cloud shielding increase. The strongest positive trends of the H_2O VCD are found over the tropical Pacific, over the Pacific south of Alaska, over North-east Greenland, and over Siberia; strong increases are also detected for large parts of all southern Oceans. Negative trends of the H_2O VCD are found over parts of North America, the Pacific west of the USA, over northern Australia, the Arabic peninsula and over the southern Atlantic close to Antarctica.
The trends of the cloud shielding show similar patterns, especially in the Tropics and in the southern hemisphere. In the northern hemisphere, however, also many differences can be

found. At several locations (e.g. over the Pacific south of Alaska) the patterns of the cloud trends seem to be slightly shifted against those of the H_2O trends. These differences might be related to the higher fraction of land surface in the northern hemisphere. One explanation could be that in contrast to the ocean, over the continents also the surface type and water availability has a strong influence on the evaporation rate. Also the long range transport and the specific precipitation history of air masses might explain part of the differences.

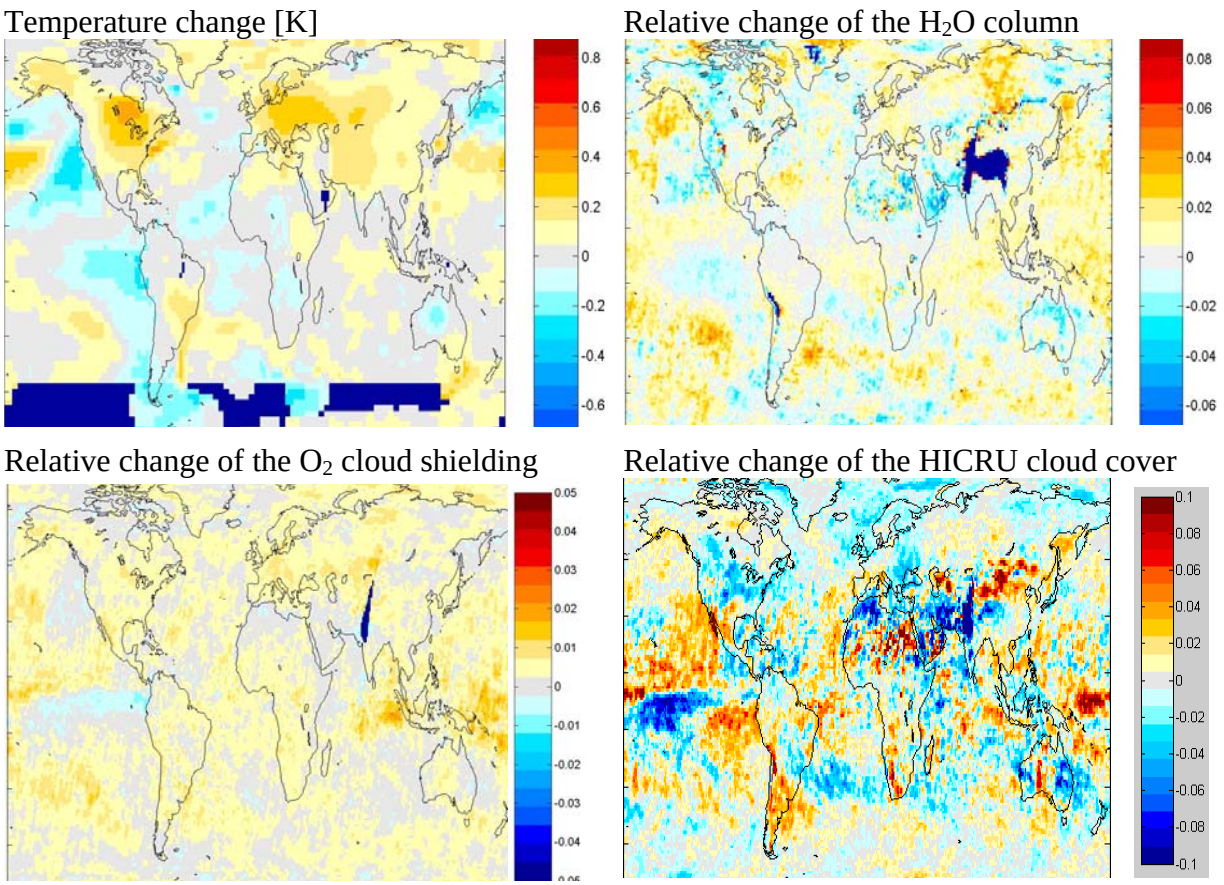

Fig. 1 Global trend patterns of yearly averaged surface near temperature, total column precipitable water and the two cloud quantities. Especially in the tropics and the southern hemisphere many similarities between the trend patterns of all data sets can be found; over the northern hemispheric continents also opposite trends occur. Dark blue color indicates areas without data.

Conclusions

From GOME satellite observations we analysed global time series of the H_2O VCD, O_2 cloud shielding (based on the O_2 absorption) and HICRU cloud fraction (based on broad band spectral measurements) for 1996-2002. The analysis of the H_2O VCD and the O_2 cloud shielding is based on the DOAS method. Thus, our analysis is almost not affected by instrument degradation and is thus in particular well suited for trend studies. In addition, it has similar sensitivity over land and ocean and can yield a consistent global picture. To minimise any influence of clouds on the H_2O trend we only investigated observations for an O_2 absorption between 80% and 95% of the maximum values of the O_2 absorption. Thus the trends for the H_2O VCD are only representative for nearly clear sky conditions. In contrast, the trends for the cloud shielding include all observations.

The spatial trend patterns of the H_2O VCD and the cloud shielding show both positive and negative trends. Especially over the tropics and the southern hemispheric oceans the trends of

the H_2O VCD are very similar to those of the cloud shielding and the surface temperatures indicating a direct relationship between surface temperatures and the hydrological cycle.
In contrast, in the northern hemisphere the correlation of the spatial patterns is worse. Especially over the continents even opposite trend patterns for the H_2O VCD and the surface temperature are found indicating that the relationship between the surface temperatures and the hydrological cycle is much more complex. This might be mainly related to the different distribution of ocean and land surfaces in both hemispheres with the evaporation over continents depending on surface type, water availability, and the yearly amplitude of the surface temperature.
The trend patterns in the tropics are similar to the anomalies during the ENSO phenomenon 1997/98 (see Wagner et al. [2005a]). Positive trends are especially found over the central Pacific where the strongest positive anomalies during the ENSO period occur.
Fortunately, there is a long temporal overlap (from mid 2002 to mid 2003) between GOME and its successor (SCIAMACHY, see Bovensmann et al. [1999]), for which nearly identical analysis procedures can be applied. Thus it will be possible to continue the GOME time series without discontinuities. A further elongation of the time series until 2020 will probably be possible including the measurements of the three instruments of the GOME-2 series [EUMETSAT, 2005].

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