Global trends (1996–2003) of total column precipitable water observed by Global Ozone Monitoring Experiment (GOME) on ERS-2 and their relation to near-surface temperature

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[¹] We have analyzed global trends of total column precipitable water from measurements of the Global Ozone Monitoring Experiment (GOME) on the European Research Satellite (ERS-2) for the period January 1996 to June 2003. In contrast to other satellite retrieval methods of total column precipitable water, our analysis does not rely on a priori assumptions or additional information; thus it is particularly well suited to trend studies. The chosen wavelength range in the red spectral region ensures similar sensitivity for observations over land and ocean and thus a consistent global picture. To minimize the influence of clouds on the water vapor trends, we selected observations under mainly clear-sky conditions. The temporal evolution of the monthly or yearly averaged total column precipitable water, especially in the tropics, is highly correlated to that of the near-surface temperature, indicating that the global atmospheric humidity is mainly driven by Clausius-Clapeyron’s principle. The magnitude of the dependence on near-surface temperature indicates a strong water vapor feedback. The spatial patterns of the water vapor trends show both positive and negative signs. Especially over the oceans, trend patterns very similar to those of near-surface temperature are found. In contrast, over Northern Hemispheric continents the trend patterns are much less correlated, and even opposite trends for water vapor and the near-surface temperatures are found. During the period 1996–2002 the globally and yearly averaged total column precipitable water increased by 2.8 ± 0.8% (excluding the ENSO period).


1. Introduction

[²] Atmospheric water vapor is the most important greenhouse gas contributing about two thirds of the natural greenhouse effect. In contrast to other greenhouse gases like CO₂ and CH₄ 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 most strongly 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]. While there have been speculations that even a negative water vapor feedback might exist [Lindzen, 1990], most studies today favor a positive feedback, and the main question is how strong this feedback actually is [e.g., Yang and Tung, 1998; Allan et al., 2002]. One important question is whether relative humidity stays constant while climate changes. Several studies indicate that relative humidity would stay constant [e.g., Soden et al., 2002] leading to a strong positive water vapor feedback. Other studies indicate that relative humidity might be reduced (increased) if temperature increases (decreases); then the relative change of the specific humidity might be smaller than the relative change of the saturation mixing ratio [e.g., Minschwaner and Dessler, 2004] and the water vapor feedback would be smaller.

[³] In contrast to previous space-borne observations of atmospheric humidity, as from the Television Infrared Observation Satellite Program (TIROS) Operational Vertical Sounder (TOVS) and from the Special Sensor Microwave/Imager (SSM/I) [Liu et al., 1992; Sun, 1993; Stephens et al., 1994, Elliot, 1995; Soden and Fu, 1995; Jackson and Stephens, 1995; Soden and Bretherton, 1996; Randel et al., 1996; Wentz, 1997; Engelsen and Stephens, 1999; Simpson et al., 2001; Soden et al., 2000; Lang, 2003, and references therein], our water vapor data set has three major...
advantages: First it covers the entire Earth, including the continents (while SSM/I observations are only reliable over oceans) leading to a much more consistent picture of the global distribution of atmospheric humidity. Second, the GOME water vapor analysis is performed in the visible spectral range. Thus for (at least partly) cloud free observations it is very sensitive also to the part of the water vapor profile close to the surface, which constitutes the major fraction of the total atmospheric column [Wagner et al., 2003, 2005]. In contrast, the sensitivity of TOVS water vapor observations decreases systematically toward the surface. Third, in contrast to most other algorithms our water vapor analysis does not rely on independent additional information or a priori assumptions [Wagner et al., 2003, 2005] and is thus especially well suited for trend studies. In particular, we can rule out that the trends derived from our data set contain possible artificial contributions caused by the influence of independent variables, like, for example, the near-surface temperature itself.

[4] However, it should be noted that the GOME measurements also have significant limitations. First, compared especially to the SSM/I observations, the spatial and temporal resolution as well as the global coverage is much coarser. Second, also the accuracy of an individual observation is, in general, modest (in particular for cloudy sky observations). GOME observations yield no profile information while from TOVS measurements different tropospheric layers can be distinguished. In addition, since GOME observations are made around local noon, especially in regions with a pronounced diurnal cycle, they might not be representative for the daily averages.

[5] Previous studies have quantified the water vapor feedback from global satellite observations. They investigated, for example, the variation of the surface near temperatures during the seasonal cycle [Yang and Tung, 1998]. Another study quantified the response of atmospheric humidity to the atmospheric cooling after the eruption of Pinatubo [Soden et al., 2002].

[6] Our observations cover a period (1996–2003), during which the globally averaged near-surface temperature showed strong variation: more than 0.3K difference in 1996 and 1998 (see, e.g., Intergovernmental Panel of Climate Change [IPCC] [2001] or results of the Climate Research Group at the Hadley Centre of the UK Meteorological Office, http://www.cru.uea.ac.uk/cru/data/temperature/[Jones and Moberg, 2003]). Thus it is possible to directly investigate the water vapor feedback as a function of time and location and, in particular, to compare it to the expectations of simple equilibrium physics (based on the Clausius-Clapeyron principle).

[7] Our paper is organized as follows: In section 2, we introduce the satellite instrument and the data analysis. The basic features of our algorithm are described in section 2.2; for most readers this section will contain sufficient information for a proper understanding of our results. The more interested reader will find many additional details, especially on the estimation of the measurement uncertainties, in sections 2.3–2.4. Section 2.5 discusses the cloud influence on our trend analysis and section 2.6 presents a comparison of our observations to other existing data sets. In section 2.7, we introduce two global data sets of near-surface temperatures. In section 3, we present the results of our trend analysis for atmospheric water vapor and relate it to trends of the near-surface temperature.

2. Instrument and Data Analysis

2.1. GOME on ERS-2

[8] The GOME instrument is one of several instruments aboard the European Research Satellite ERS-2 [Bednarz, 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 by means of 4096 spectral channels covering the wavelength range between 240 and 790 nm with moderate spectral resolutions. While GOME was primarily designed for the observation of the ozone layer, in addition, many other trace gases can be also analyzed from the spectra, several of them for the first time from space [e.g., Burrows et al., 1999]. The satellite operates in a nearly polar, Sun-synchronous orbit at an altitude of 780 km with an equator crossing time of approximately 10:30 a.m. local time. While the satellite orbits the Earth in an almost north-south direction, the GOME instrument scans the surface of the 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 central, and an eastern pixel. The Earth’s surface is totally covered within 3 days (poleward from about 70° latitude within 1 day). During this three day orbital repetition pattern, the local equator crossing time varies by about ±35min. Over the period under consideration (1996–2003), these patterns of equator crossing times stayed constant.

[9] It is important to note, that especially in regions with a pronounced diurnal cycle of the total column precipitable water, GOME observations might be systematically offset compared to observations made at other fixed times (or performed continuously during day and night).

2.2. H2O Retrieval From GOME Spectra

[10] Several algorithms for the retrieval of the total column precipitable water in the visible part of the spectrum from GOME were developed during recent years [Noël et al., 1999, 2000, 2002; Casadio et al., 2000; Maurellis et al., 2000; Lang et al., 2003; Lang, 2003; Wagner et al., 2003, 2005; Lang and Lawrence, 2005]. In contrast to these 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. One specific advantage of the DOAS method is that it is sensitive to relative (differential) absorptions; thus our water vapor results are almost independent of instrument degradation (for details, see section 2.3).

[11] In this study, we present a modified retrieval with respect to Wagner et al. [2003, 2005], which is especially suited for the analysis of trends. While the spectral analysis is almost unchanged (for details, see Wagner et al. [2003, 2005]) we now utilize the measured O2 absorption (instead of the absorption of the oxygen dimer O4) for the correction of atmospheric radiative transfer modifications, e.g., due to clouds. Compared to the O4 absorption, that of the molec-
ular $O_2$ absorption is much stronger (several ten percent instead of only a few percent for the spectral resolution of GOME) and shows a much more characteristic spectral structure. Thus it can be analyzed with substantially higher precision, which is of paramount importance for trend studies.

[12] The desired total column precipitable water (TCPW) is the vertically integrated water vapor concentration (in DOAS remote sensing literature it is often referred to as vertical column density VCD). It is calculated as follows:

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

Here $SCD_{H_2O}$ and $SCD_{O_2}$ are the measured slant column densities (the integrated concentration along the light path) of water vapor and $O_2$, respectively. The $VCD_{O_2}$ is calculated from an average atmospheric pressure profile. The ratio of the $SCD_{O_2}$ and $VCD_{O_2}$ defines the air mass factor ($AMF_{O_2}$) [Solomon et al., 1987; Marquard et al., 2000; Wagner et al., 2003], which is used for the conversion of the measured $SCD_{H_2O}$ into the desired total column precipitable water ($VCD_{H_2O}$). It is important to note that usually, the air mass factor is derived from numerical radiative transfer modeling. In contrast, here we derive a “measured” air mass factor from the simultaneously measured $SCD_{O_2}$. The underlying assumption is that $AMF_{O_2}$ is similar to the AMF for water vapor (see below). 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).

[13] Although the effects of clouds on the measured total column precipitable water are basically corrected by the application of the measured air mass factor, potential systematic cloud effects might still appear due to the different altitude profiles of $H_2O$ and $O_2$ [Wagner et al., 2003, 2005]. Thus, for the trend analysis, only mainly cloud free observations were used (where the $O_2$ absorption is between 80 and 95% of the maximum $O_2$ absorption). The application of both, a lower and an upper threshold ensures that systematic changes of the cloud cover during the observed time period have almost no influence on the derived total column precipitable water trends (for details of the cloud effect, see section 2.5).

[14] It should be noted, that while in the meteorological literature the total column precipitable water is usually expressed in units of g/cm$^2$, in DOAS related publications it is often expressed as vertical column density in units of molecules per cm$^2$ (1g/cm$^2$ corresponds to $3.3 \times 10^{22}$ molec/cm$^2$). In this study, we generally use the term total column precipitable water and the unit of g/cm$^2$; in several figures both units (molec/cm$^2$ and g/cm$^2$) are shown.

[15] From detailed sensitivity studies, we determined an upper limit of about 2% for the precision of the water vapor DOAS analysis (see section 2.3). The water vapor trend studies over 6 years are even less affected: for the spatial trend patterns, or data averaged over selected latitude bands or the whole globe the uncertainty is smaller than 0.8%.

[16] For the spectral resolution of the GOME instrument, the temperature dependence of the $H_2O$ and $O_2$ cross sections are about $-0.15\%/K$ and $-0.03\%/K$, respectively. These weak temperature dependences partly cancel out in equation (1) and the remaining temperature dependence of the total column precipitable water is by far too weak (and also in the inverse direction) to explain the observed dependence on near-surface temperature.

### 2.3. Analysis Details and Error Estimation

[17] Using the approach of measured air mass factors 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). Nevertheless, because of the differences in the atmospheric profiles of $O_2$ (or $O_4$) and $H_2O$, also systematic differences can occur [see Wagner et al., 2003, 2005]. Compared to $O_4$ (which was used in our original water vapor retrieval), the atmospheric $O_2$ concentration profile deviates even more strongly from that of water vapor. Nevertheless, the much stronger and characteristic absorption feature of the molecular oxygen absorption leads to a substantially better measurement precision compared to the use of the dimer absorption. In particular, the $O_2$ absorption is nearly unaffected by changes in the etalon structure after an instrument switch-off (etalon structures are caused by optical interference effects originating at thin layers of the detector coating and the ice cover on its surface, see Bednarcz [1995]). To minimize any remaining influence of a changing etalon structure, the degree of the polynomial used in the DOAS analysis is set to 8. Because of the use of the atmospheric $O_2$ absorption (instead of $O_4$), some corrections have to be applied to the retrieved total column precipitable water.

[18] 1. Because of the deviation of the atmospheric $O_2$ concentration profile (scale height about 8 km) from that of water vapor (scale height of about 1 km), the measured AMF derived from the $O_2$ absorption is in general larger than the correct AMF for water vapor. From radiative transfer simulations we find that it is in general about 15–35% larger (depending on the measurement conditions) than that for water vapor. From the comparison with other independent observations (see section 2.6) we indeed found a systematic deviation of about 33%. We thus decided to apply a correction of $+33\%$ to our whole data set of GOME total column precipitable water. It should be noted that this correction, in fact, introduces independent information to our data set. Nevertheless, the application of a constant correction factor to the whole data set does not affect at all the calculation of relative trends from the GOME observations.

[19] It should be noted that due to the different profile shapes of water vapor and $O_2$, clouds can also lead to potentially large deviations of the retrieved total column precipitable water from the true value in specific situations (in particular for low clouds and large cloud fractions; also high aerosol amounts can have a similar effect). It is interesting to note here that our original total column precipitable water product from GOME using $O_4$ absorption is less strongly affected by this source of error, because the $O_4$ concentration profile (scale height of about 4 km) is closer to that of water vapor. Thus for an individual observation (especially for clouded scenes), in general, the GOME water vapor product derived using the $O_4$ absorption
can be expected to have a higher accuracy. Nevertheless, because of the better precision of the analysis of the \( \text{O}_2 \) absorption, the GOMe water vapor product derived using the \( \text{O}_2 \) absorption also has a much higher precision, especially when averaged over a large number of observations. Thus relative changes can be much better identified, which is of paramount importance for trend studies.

2. Since the fine structured \( \text{O}_2 \) absorption is not fully resolved by the GOMe instrument, the \( \text{SCD}_{\text{O}_2} \) derived from the DOAS fit (like the \( \text{SCD}_{\text{H}_2\text{O}} \)) is no longer a linear function of the true atmospheric \( \text{SCD}_{\text{O}_2} \). We correct this “saturation effect” by modeling the nonlinearity as described for water vapor by Wagner et al. [2003]. The corrected \( \text{SCD}_{\text{H}_2\text{O}} \) and \( \text{SCD}_{\text{O}_2} \) are then actually used for equation (1).

21 Because of the strength and the characteristic fine structured spectral shapes of the absorptions of \( \text{O}_2 \) and \( \text{H}_2\text{O} \), the respective results of the spectral analysis have only small uncertainties. For the \( \text{O}_2 \) absorption the statistical uncertainty is usually <1%; for \( \text{H}_2\text{O} \) it is usually between <1% at low latitudes and <5% at high latitudes. However, especially for the mean values of large data sets, as analyzed in this trend study, these statistical errors are of no relevance. More important are possible remaining systematic errors, especially if they change with time. Possible systematic errors are discussed in the following.

22 In order to minimize possible systematic errors caused by a spectral drift of the instrument, special care was taken for the wavelength calibration of the individual spectra:

23 In the first step, a selected direct Sun spectrum is fitted (wherein the spectral convolution, and spectral shift and squeeze are optimized [see, e.g., Allwell et al., 2002]) to a high-resolution solar spectrum [Kurucz et al., 1984], providing an absolute wavelength calibration for the direct Sun spectrum. In a second step, the direct Sun spectrum of an individual day is fitted (with spectral shift and squeeze allowed) to the selected direct Sun spectrum (from step 1) to correct any possible spectral drift of the instrument. This is done in the same way for all direct Sun spectra of all days. In the final DOAS analysis (step 3), the Earth shine measurement is fitted (with spectral shift and squeeze allowed) to the direct Sun spectrum of the same day (and the trace gas reference spectra). This procedure has the advantage of full consistency of the spectral calibration over the entire time series with similarly optimum convergence of the spectral DOAS fit (because the direct Sun spectrum of the same day is used). A precise spectral calibration is particularly important for the analysis of trends since even slight shifts in the spectral calibration can significantly influence the retrieved absorptions of atmospheric species. It should be noted that during the period from summer 2002 to the end of 2003, no daily direct Sun spectra are available for GOMe. For this period we performed two analyses, one with a Sun spectrum from summer 2002, and another with a solar spectrum from November 2003. We used the average of both time series for the period summer 2002 to end of 2003.

24 The use of a DOAS retrieval and the particular choice of the fitting parameters as described above makes the water vapor analysis very insensitive to any potential instrumental degradation effects. In particular, for the DOAS analysis of narrow spectral features (of water vapor and \( \text{O}_2 \)), any loss of broad band sensitivity of the detectors cancels out. In addition, even spectral degradation features mostly cancel out because they affect the atmospheric spectrum and the direct Sun spectrum in the same way. There remain two known error sources, which might affect the atmospheric spectra and the Sun spectra in a different way: potential changes of the spectral polarization sensitivity of the instrument and artificial spectral structures caused by the diffuser plate [Richter and Wagner, 2001; Richter and Burrows, 2002; Richter et al., 2002].

25 We quantified such remaining error sources by comparing the water vapor results with a second analysis, which was performed using only one selected direct Sun spectrum (from July 1997) for the DOAS analysis of the whole time series (see also section 2.3). From the differences between both analyses, we determined an upper limit for the error of the water vapor DOAS analysis of about 2%. From the comparison of both analyses, we also estimated the error of our trend analysis: for studies of the temporal correlation (section 3.2), the error of the derived temperature dependence of the total column precipitable water is <12% for the whole globe, <3% for the tropics (relative error of the regression line). For the trends calculated over the entire period 1996–2002 (as for the spatial trend patterns, see section 3.3), the errors are even smaller: they are <0.8% (absolute error of the relative trend of the total column precipitable water over 6 years). It should particularly be taken into consideration that these values represent upper limits of the errors. The errors of the second analysis can be expected to be larger than those of the original analysis, because no daily reference spectra were used.

2.4. Instrumental Stability

26 The assessment of the instrumental stability is of crucial importance for any trend analysis. One important advantage of the DOAS analysis is that it is not affected by any degradation of the broad band spectral sensitivity of the instrument. However, since GOMe is a complex spectrometer, it cannot be ruled out that during the years, the degradation process might affect also narrow band spectral structures, which could have a systematic effect on the analyzed total column precipitable water. An elegant way of investigating the stability of the GOMe instrument with respect to narrow band spectral features is to investigate the temporal changes in the optical depths of the Fraunhofer lines. Since the optical depth of the Fraunhofer lines hardly changes with time, any deviation from the average value can be seen as an indicator of instrumental change.

27 To quantify the instrumental stability we analyzed the Fraunhofer line at 658 nm. For the spectral resolution of GOMe in the red spectral range (0.33 nm FWHM), its optical depth is 0.434.

28 We investigated the time series of the analyzed optical depth for the two DOAS analysis (either with daily or fixed direct Sun spectrum, see section 2.3). Our interpretation is as follows: when using a daily direct Sun spectrum, most changes of the instrumental performance affect the solar spectra and the Earth shine spectra in a similar way. In addition, assuming, e.g., that the optical depths of the Fraunhofer lines change during the solar cycle, this would also affect both, the direct solar spectrum and the...
Earth shine spectrum, in a similar way and also cancels out in the DOAS analysis. From the analysis using a daily direct Sun spectrum, we find a relative trend over 7 years of only 0.008% to 0.014%. This very small trend illustrates the high stability of the GOME instrument and the DOAS analysis of narrow spectral features over a long instrumental lifetime in space.

From the second analysis using a fixed direct Sun spectrum, we find a slightly larger (negative) trend over 7 years between 0% and -0.056%. This higher (but still very small) trend could be the result of possibly changing instrumental properties (like dark current of the detector) or changing solar properties during the solar cycle, which no more cancel out when a fixed direct Sun spectrum is used.

We conclude that instrumental degradation is much smaller than the analyzed trends of the total column precipitable water. It may also be interesting to note that we find no spatial correlation between the patterns in the trends of the optical depth of the Fraunhofer line at 658 nm and the total column precipitable water.

2.5. Cloud Effects on the Water Vapor Data

For satellite observations, clouds shield the underlying atmospheric absorptions. Although the concept of measured air mass factors (see equation (1)), in general, corrects for the basic effects of clouds, because of the different atmospheric height profiles of H₂O and O₂, potential systematic effects can still remain [Wagner et al., 2005]. Thus a changing cloud cover might lead to an apparently changing amount of total column precipitable

Figure 1. Global trend patterns of yearly averaged total column precipitable water for different selections of the cloud cover (categorized by the O₂ absorption): high O₂ absorptions indicate clear-sky conditions while the shielding effect of clouds leads to a decreased O₂ absorption. We selected the measurements according to a lower and upper threshold expressed relative to the maximum O₂ absorption. The trends are expressed as relative trends per year. Dark blue color indicates areas without data.
water in our data set. To minimize the effects of clouds on the
determined water vapor trends, we decided to exclude the
observations with strong cloud shielding ($O_2$ absorption $>$
lower threshold). In addition, we excluded measurements for
(almost) cloud free conditions ($O_2$ absorption $<$ upper
threshold) in order to prevent that a changed frequency of
totally clear-sky measurements affects the derived trends.

For the determination of the thresholds, several aspects have
to be considered. First, observations with large cloud frac-
tion should be excluded in order to minimize any influence
of a changing cloud cover on the derived trends of the total
column precipitable water. Hence the lower threshold should
be rather high. Second, although the upper threshold should
be low enough to avoid totally clear pixels, it should be also
as high as possible to minimize the influence of clouds.
Third, the gap between the thresholds should be large
enough to allow sufficient GOME observations to fulfill
these selection criteria. In order to determine well suited
upper and lower thresholds, we calculated trends for differ-
ent selected values (Figure 1). While the trend patterns are
similar for all selections, the strength of the trends varies
slightly for the various selections. In general, we find that
the trends are smallest, if all observations are included
(lower threshold = 0). This indicates that for large cloud
cover, a change in the total column precipitable water is
accompanied by a partly compensating change in cloud
cover: if the total column precipitable water increases, also
the cloud cover increases leading to an increased shielding
effect and thus decreasing the observed water vapor trend.

In addition to this shielding effect of clouds on the retrieval,
part of the difference may be also caused by the dependence
of atmospheric humidity on cloud cover [Gaffen and Elliott,
1993]. It is, however, interesting to note that the strongest
trends are not found for the highest values of the lower
threshold. From our observations, we cannot judge whether
the slightly higher trends for larger cloud fractions are real
or due a remaining cloud effect on our observations.

Nevertheless, the most important result of our sensitivity
studies is that the fine-tuning of the thresholds has no
substantial influence on the basic trend patterns. From our
sensitivity studies, we chose (with some remaining arbi-
trariness) a lower threshold of 80% of the maximum $O_2$
absorption and an upper threshold of 95% of the maximum
$O_2$ absorption. Since measurements with strong cloud
shielding are excluded from the trend analysis, the derived
water vapor trends are representative for mainly cloud free
conditions.

2.6. Comparison to Other Satellite Data

[32] Figure 2 (left) shows the correlation of monthly
mean total column precipitable water measured by SSM/I
and GOME. For this comparison, we selected daily obser-
vations of the SSM/I instrument F10 in ascending mode
(version 5, data are from http://www.ssmi.com/) made
about one hour before GOME overpasses. Both data sets were
represented on a $0.5\degree \times 0.5\degree$ grid. It should be noted that the
SSM/I observations sample all atmospheric conditions
while for the GOME observations only mainly cloud free
scenes during daytime are analyzed (see section 2.5).
Detailed information on the SSM/I data set and its valida-
tion can be found by Liu et al. [1992], Sun [1993], and
Wentz [1997].

[33] In order to investigate the potential influence of the
different sampling conditions, we also performed a second
comparison using daily observations of both sensors
(Figure 2, right). In this case, it is possible to select
only coincident observations of both sensors. Interestingly,
also for the comparison of the coincident observations,
we find nearly identical results as in the case of the monthly
mean data. As stated in section 2.3, the GOME total column
precipitable water derived from equation (1) is systematically
too low because of the different sensitivity for the profiles of
water vapor and O\(_2\). From the comparison of SSM/I and GOME observations, we chose a correction factor of 1.33 (which is already applied to the GOME data shown in Figure 2). It is interesting to note here, that this correction factor actually introduces independent information to our data set. However, since the same correction factor is applied to the whole data set, the derived trends are not affected by this correction.

We also compared the results of our algorithm to those of the NASA Water Vapor Project (NVAP) data set (e.g., http://eosweb.larc.nasa.gov/PRODOCS/nvap/table_nvap.html). Besides observations from SSM/I, the NVAP data set also contains observations from radio sondes and satellite observations made in the thermal infrared. The latter is the dominant source of information for the NVAP data set over the continents. Detailed information on the NVAP data set and its validation is given by Randel et al. [1996] and Vonder Haar et al. [2003]. Global annual mean values of the NVAP total column precipitable water are presented by Vonder Haar et al. [2005] for the period 1998–1999. For the 4 years of overlap with the GOME data, we find a similar temporal variation (the correlation analysis yields a slope of 1.00 and \(r^2\) of 0.95), but a small bias of about 3%. It should be noted that also for the years 2000 and 2001 NVAP data are available [Vonder Haar et al., 2003] agrees well with those derived from the GOME observations.

The bias between the NVAP and the GOME data might be partly caused by the measurements over the continents, which were not included in the comparison to SSM/I data. Over the continents, in general, the diurnal variation of temperature and thus also of total column precipitable water is larger than over the oceans. The higher values of the GOME data might thus be related to the fact that they only contain daytime observations, while the NVAP measurements were also made during night. An additional reason for the differences over continents might also be related to differences between the cloud effects (and their corrections) in the visible and the infrared spectral ranges. Nevertheless, it should be noted that a small bias does not substantially affect the trend analysis.

It is interesting to note here that also the temporal evolution of the monthly anomalies of the total column precipitable water of the NVAP data set [Vonder Haar et al., 2003] agrees well with those derived from the GOME observations.

2.7. Data Sets for Near-Surface Temperature

In section 3, we will compare the global trends of our total column precipitable water to trends of near-surface temperatures. We use temperature data from two different sources.

1. The first is near-surface temperature anomalies (with respect to the monthly averages from 1961 to 1990) analyzed by the Climate Research Group at the Hadley Centre of the UK Meteorological Office (HadCRUT2(v), see http://www.cru.uea.ac.uk/cru/data/temperature/). They are derived from station measurements of the air temperature for land, and from observations of the sea surface temperature from ships during night over the oceans; details on this data set of near-surface temperatures are given by Jones and Moberg [2003]. We refer to these temperature data as HADCRU temperatures in the following.

2. The second is near-surface temperature anomalies from the Goddard Institute for Space Studies (GISS), see http://www.giss.nasa.gov/data/update/gistemp/). One important difference with regard to the HADCRU data is the use...
of satellite observations of nighttime sea surface temperatures over the oceans, see Hansen et al. [2001] and Reynolds et al. [2002]. We refer to this temperature data set as GISS temperature in the following.

[40] It is interesting to note that from the correlation of the monthly anomalies of both temperature data sets, we find substantial differences: the amplitude of the time series (January 1996 to June 2003) of the GISS temperature anomalies is higher (by about 11% for the whole globe and 8% for the tropics); \( r^2 \) between both data sets is only 0.79 for the whole globe and 0.93 for the tropics.

[41] For the analysis of the temporal correlation between total column precipitable water and near-surface temperature, we use both data sets (section 3.2). For the analysis of the spatial correlation (section 3.3) we use only the GISS data set, for which spatially resolved data of near-surface temperature trends were available.

3. Results

3.1. Latitudinal Averaged Time Series

[42] In Figure 3, the monthly mean atmospheric total column precipitable water for the period 1996–2003 is presented as a function of latitude (10° bins) and time. The total column precipitable water averaged over the entire globe or hemispheres is shown in Figure 4.

[43] Several interesting features of the hydrological cycle can be identified. In both hemispheres, the total column precipitable water distribution follows the seasonal cycle of the near-surface temperatures. The tropical total column precipitable water amplitude of the yearly cycle in the Northern Hemisphere is about twice the amplitude of the Southern Hemisphere.

Figure 4. Time series of monthly averaged total column precipitable water for both hemispheres and the whole globe. The amplitude of the yearly cycle in the Northern Hemisphere is about twice the amplitude of the Southern Hemisphere.

Figure 5. (left) Time series of monthly anomalies of the globally averaged temperature and total column precipitable water. The temperature anomalies are calculated relative to the monthly average values of the period 1961–1990 (see http://www.cru.uea.ac.uk/cru/data/temperature/). The total column precipitable water anomalies are calculated relative to the monthly average values of the period 1996–2002. (right) Correlation analysis of both data sets.
precipitable water has a minimum during Northern Hemispheric winter. During 1997/1998, the strong ENSO phenomenon leads to significantly higher tropical values compared to other years [Wagner et al., 2005]. The maximum values and amplitude of the seasonal cycle of the total column precipitable water in northern middle and high latitudes is systematically larger than in the Southern Hemisphere, mainly reflecting the higher fraction of continental landmass in the Northern Hemisphere.

3.2. Temporal Evolution

In this section, we analyze trends for total column precipitable water averaged over selected latitude bands or for the whole globe. Similar studies have been performed for the seasonal variation of temperature [Yang and Tung, 1998], and also for the systematic atmospheric cooling after the eruption of Mount Pinatubo [Soden et al., 2002]. Here we investigate the correlation of the monthly anomalies for a period (1996–2003), during which the global near-surface

![Figure 6](image6.png)

Figure 6. Same as Figure 5 but for the tropics (latitude between 30°N and 30°S).

![Figure 7](image7.png)

Figure 7. Vertical profiles used for the simulation of the tropical total column precipitable water. (left) Relative humidity as given by Minschwaner and Dessler [2004]. (right) Water vapor concentration (specific humidity) calculated according to the relative humidity profile and assuming a moist adiabatic lapse rate of −0.65 K/100 m for surface temperatures of 24°C (blue line) and 25°C (red line).
Figure 8. (top) Yearly global averages of the total column precipitable water and the near-surface temperature (from http://www.cru.uea.ac.uk/cru/data/temperature/). During the ENSO years 1997/1998 the average of the first half of 1997 and the second half of 1998 is used as one data point for both years 1997/1998 (blue points). From these data, linear trends were calculated. For completeness, the average values for the single years 1997 and 1998 are also shown as red points. (bottom) Correlation analysis of all yearly averages (also for the ENSO period).

Northern mid and high latitudes $>30^\circ$N  Southern mid and high latitudes $<30^\circ$S

Figure 9. Correlation between the monthly averaged values of the total column precipitable water and the near-surface temperature anomalies for latitudes (left) $>30^\circ$N and (right) $<30^\circ$S. The temperature data are from http://www.cru.uea.ac.uk/cru/data/temperature/. In contrast to the tropics, almost no correlation was found.

Figure 10. Global trend patterns of yearly averaged total column precipitable water and near-surface temperature (from http://www.giss.nasa.gov/data/update/gistemp/[Reynolds et al., 2002]). Especially in the tropics and the Southern Hemisphere, many similarities between the trend patterns of the total column precipitable water and the temperature are found. Over the Northern Hemispheric continents, opposite trends also occur. The trends of the total column precipitable water are expressed as relative trends per year. Dark blue color indicates areas without data.

temperatures showed a strong variation [see, e.g., IPCC, 2001].

[45] In Figure 5, the time series of anomalies of the globally and monthly averaged total column precipitable water with respect to the monthly mean values from 1996 to 2002 are presented. Also shown are the globally averaged anomalies of the HADCRU near-surface temperatures. Both time series show a similar temporal evolution, with enhanced values of total column precipitable water during periods of enhanced near-surface temperatures and vice versa [see also Vonder Haar et al., 2003]. We find that the total column precipitable water increases by about 0.19 g/cm² (6.4 × 10⁻¹¹ mole/cm²) per K temperature increase. This corresponds to a relative increase of 8% per K temperature increase. The correlation coefficient r² is 0.45 and the uncertainty of the regression line for the 95% confidence interval is 24%.

[46] An even more pronounced correlation of the total column precipitable water and near-surface temperature is found if the mean values for the tropics are calculated (30°N–30°S; see Figure 6). We find that the total column precipitable water increases by 0.29 g/cm² (9.6 × 10⁻¹¹ mole/cm²) per K temperature increase. Again, this corresponds to a relative increase of 8% per K temperature increase. However, for the tropics the correlation coefficient is larger (r² = 0.57) and the uncertainty of the regression line for the 95% confidence interval is only 18%.

[47] We performed a similar correlation study also with the GISS temperature data set of near-surface temperature anomalies. For the tropics, we find almost the same result (an increase of 0.28 g/cm² (9.4 × 10⁻¹¹ mole/cm²) per K temperature increase, and r² = 0.58. In contrast, for the whole globe, the temperature dependence is substantially smaller (−7%) than for the HADCRU data set. Also the correlation is weaker (r²: 0.37 instead of 0.45) (see also section 2.7).

[48] We compare the determined dependence of the total column precipitable water on near-surface temperature with the expectations from the Clausius-Clapeyron principle. For that purpose, we applied a simple model of tropical tropospheric humidity. Following Minschwaner and Dessler [2004], we assumed a tropospheric profile of relative humidity as shown in Figure 7. We then assumed a temperature profile following a moist adiabatic lapse rate of −0.65 K/100 m. From both assumptions, we calculated the height profile of the water vapor concentration (specific humidity) for different assumed near-surface temperatures (Figure 7). We integrated these profiles to calculate the corresponding total column precipitable water; for an assumed near-surface temperature of 24°C, we derive a total column precipitable water content of 3.60 g/cm² (1.20 × 10⁻¹¹ mole/cm²). This value is similar to the average total column precipitable water over the tropics (30°N–30°S) as derived from our measurements. If we increase the near-surface temperature by 1 K, but leave the tropospheric relative humidity profile unchanged, the integrated total column precipitable water increases to 3.86 g/cm² (1.29 × 10⁻¹¹ mole/cm²). Thus we end up with an increase in total column precipitable water of 0.26 g/cm² (8.6 × 10⁻¹¹ mole/cm²) per K, which is slightly less than the observed value of 0.29 g/cm² (9.6 × 10⁻¹¹ mole/cm²) per K. We also calculated the increase of the total column precipitable water under the assumption that below 2.5 km the relative humidity stays constant (equivalent to a decrease of the relative humidity by about 2 to 4%). This case should represent the hypothesis that an increased near-surface temperature might lead to a decrease in relative humidity in the middle and upper troposphere [Lindzen, 1990; Held and Soden, 2000]. For this case, the increase in total column precipitable water is only 0.20 g/cm² (6.8 × 10⁻¹¹ mole/cm²), thus substantially smaller than the observed value. It is interesting to note here that the assumed lapse rate of −0.65K/100 m may not be perfectly appropriate for the selected satellite observations including mainly cloud free observations. Nevertheless, even if we assume different lapse rates, the results do not change substantially: for lapse rates of −0.5 K/100 m or −0.8 K/100 m the increase of the total column precipitable water for the case of constant humidity is almost identical to the results for a lapse rate of −0.65 K/100 m.
of $-0.65$ K/100 m. For a fixed specific humidity above 2.5 km, we find increases of 18.3 g/cm$^2$ ($-0.5$ K/100 m) and 22 g/cm$^2$ ($-0.8$ K/100 m), which are still not sufficient to explain the observed value of 0.29 g/cm$^2$.

[49] From our considerations we conclude that the observed dependence of tropical total column precipitable water on near-surface temperature agrees better with the assumption that the relative humidity profile stays unchanged in a changing near-surface temperature. Such a scenario is characterized by a strong increase of the specific humidity not only in the lowest atmospheric layers, but also in middle and upper troposphere, causing a strong water vapor feedback [Held and Soden, 2000], if the near-surface temperature increases.

[50] We also compared the time series of the yearly mean values of globally averaged temperatures and total column precipitable water (Figure 8). Both time series show a very similar temporal evolution. For total column precipitable water, we determined a positive trend for the period 1996–2002 (excluding the ENSO period) of about 2.8%. The yearly averaged values of temperature and total column precipitable water correlate even more strongly than the monthly mean values. We find that the total column precipitable water increases by about 0.30 g/cm$^2$ ($10.0 \times 10^{21}$ molec/cm$^2$) per K temperature increase (relative in-

**Figure 11.** Global trend maps as in Figure 10, but for different seasons.
crease: 12%). It is interesting to note that this dependence is substantially stronger compared to that for the monthly anomalies. The differences are most probably caused by the fact that for yearly mean values the temperature and total column precipitable water are averaged over different seasons. Because of the strong nonlinearity of the Clausius-Clapeyron principle, the warmer seasons will thus be more strongly weighted.

[51] In contrast to the tropics, the extratropical data sets (latitude bands >30°N and <30°S) of the total column precipitable water and near-surface temperature show almost no correlation (Figure 9).

3.3. Spatial Trend Patterns

[52] In this section we compare global maps of trend patterns for total column precipitable water and near-surface temperature (from the Goddard Institute for Space Studies (GISS), see Hansen et al. [2001] and Reynolds et al. [2002] and http://www.giss.nasa.gov/data/update/gistemp/) for the period 1996–2002. In Figure 10, trend maps for the monthly mean data are shown. Positive trends of the total column precipitable water are found over the western tropical Pacific, over the Pacific south of Alaska, over Siberia; strong increases are also detected for large parts of all southern oceans. Negative trends of the total column precipitable water 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.

[53] Especially over the oceans, the trend patterns of total column precipitable water and near-surface temperature are very similar. In contrast, over the continents, the correlation is substantially worse and even opposite trends are often found (e.g., over Northern America). These differences might be related to the fact, that in contrast to the ocean, the total column precipitable water over the continents is strongly influenced by long-range transport and the specific precipitation history of air masses. Also surface type and water availability has a strong influence on the evaporation rate.

[54] Compared to the yearly trends, the seasonal trends (Figure 11) are similar, but show larger (positive and negative) amplitudes. Again, good correlation between both data sets is found only over the oceans.

[55] In Figure 12 and Table 1, the results of the correlation analysis between total column precipitable water and

Figure 12. Correlation analysis of the spatial patterns of the trends of total column precipitable water and temperature (on a 2° grid) for different latitude bands over oceans and continents. Only over the oceans do both data sets show substantial correlation.
the temperature for different seasons and latitude bands over oceans and continents are shown. The best correlation is in general found over the tropical oceans. There, the relative increase of the total column precipitable water per K temperature increase is about 5.6% (equivalent to about 2.13 g/cm² or 7.1 × 10¹⁷ molec/cm²). It is interesting to note that a pronounced correlation is also found over the continents during summer.

4. Conclusions

We have analyzed global time series from GOME satellite observations of the total column precipitable water for the period January 1996 to June 2003. In contrast to other algorithms, our analysis directly applies the DOAS method to the measured spectra and does not rely on a priori assumptions or additional information (excepting the application of a constant correction factor derived from comparison to SSM/I data, see section 2.6). This makes our analysis particularly well suited for trend studies. Since we analyze characteristic differential absorption structures, our data set is almost unaffected by instrumental degradation. One specific advantage of the water vapor analysis in the red spectral region is that it is sensitive to the water vapor concentration close to the surface and that it has the same sensitivity over land and ocean and can thus yield a consistent global picture.

To minimize the influence of clouds on the water vapor trend, we only investigated observations for an O₂ absorption between 80% and 95% of the maximum O₂ absorption; thus our GOME data set of total column precipitable water is representative only for almost cloud free conditions around local noon.

From our time series, we calculated monthly mean anomalies for the period 1996–2002. We find that these anomalies correlate well with anomalies of the near-surface temperature (r² = 0.44 for the whole globe, r² = 0.57 for the tropics). For the tropics we find an increase in total column precipitable water of 0.29 g/cm² (9.6 × 10²¹ molec/cm²) per K temperature increase (about 8%). This is in accordance with the assumption that the relative humidity stays constant for a changed near-surface temperature and thus with the assumption of a strong water vapor feedback. This finding agrees well with those of Soden et al. [2002]. For the whole globe, the relative increase in total column precipitable water per K temperature increase is comparable or even larger (8% and 12% for the monthly and yearly averages, respectively) as would be expected from the Clausius-Clapeyron principle for lower temperatures.

The spatial trend patterns of the total column precipitable water for the period 1996–2002 show both, positive and negative signs. Especially over the oceans, the trends of the total column precipitable water are correlated to those of the near-surface temperatures. In contrast, over the Northern Hemisphere continents, even opposite trend patterns for the total column precipitable water and the near-surface temperature are found, indicating that the relationship between the near-surface temperatures and the hydrological cycle is much more complex.

From 1996 to 2002 the global yearly averages of the total column precipitable water increased by 2.8% (excluding the ENSO period). During the same period, the global yearly averaged temperature increased by 0.175 K.

The trends derived from GOME observations cover only the period 1996–2003. In summer 2003, the global measurements by GOME came to an end because of break down of the on board storage unit (the instrument itself is still in operation and observations close to ground receiving stations can still be obtained). Fortunately, there is a long temporal overlap (from mid 2002 to mid 2003) between GOME and its successor, the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), launched on ENVISAT in March 2002 [Bovensmann et al., 1999], to which nearly identical analysis procedures can be applied. Thus it will be possible to extend the GOME time series into the future without interruption. A further extension of the time series until 2020 will probably be possible by including the measurements of the three instruments of the GOME-2 series (EUMETSAT, GOME-2 products guide, http://www.eumetsat.int/).

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References


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Table 1. Correlation Analysis of the Spatial Patterns of the Total Column Precipitable Water and Temperature (on a 2º Grid) for Different Seasons Over Oceans and Continents

<table>
<thead>
<tr>
<th>Season</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>4.8%, R² = 0.095</td>
<td>4.0%, R² = 0.067</td>
<td>4.3%, R² = 0.062</td>
<td>6.0%, R² = 0.089</td>
<td>3.4%, R² = 0.105</td>
</tr>
<tr>
<td>Continents</td>
<td>2.0%, R² = 0.021</td>
<td>6.4%, R² = 0.171</td>
<td>2.1%, R² = 0.017</td>
<td>-1.1%, R² = 0.000</td>
<td>1.1%, R² = 0.010</td>
</tr>
</tbody>
</table>

*Displayed are the relative change in the total column precipitable water per Kelvin and the correlation coefficient.*


