TOTAL OZONE TRENDS DERIVED FROM THE 14-YEARS MERGED GOME/SCIAMACHY/GOME-2 DATA RECORD

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ABSTRACT

The stratospheric ozone layer is affected by a variety of factors including natural fluctuations (e.g. the 11-year solar cycle, the equatorial quasi-biennial oscillation, and volcanic eruptions), as well as the emission of ozone depleting substances (ODSs). Although the Montreal Protocol now controls the production and release of those ODSs, the timing of ozone recovery is still unclear.

Global long-term observations with space-borne instruments are essential to monitor the further evolution of the stratospheric ozone layer, and they are supplementary to well maintained ground-based measurements. For this study total ozone columns from three European satellite sensors GOME, SCIAMACHY, and GOME-2 are merged into a self-consistent long-term ozone data record starting in 1995. Global ozone trends are then estimated by applying a linear regression model to the merged time series.

A global slightly positive trend (<1% per decade) in the total ozone from the last 14 years was found, with marked positive and negative regional patterns. Results are compared to both a second global long-term satellite dataset and to ground-based data.

1. TOTAL OZONE DATASETS

Fourteen years, covering the period from June 1995 to April 2009, of monthly means of total ozone columns from three different data sources are used in this study.

Homogenized global measurements from three European satellite sensors GOME/ERS-2, SCIAMACHY/ENVISAT, and GOME-2/MetOp-A (see [3] for more details), as well as similar data products obtained from a combination of TOMS, SBUV(/2), and OMI measurements [5]. These two combined data records will be referred in this work as merged GOME and merged TOMS datasets. Additionally ground-based observations from about 70 stations distributed over the whole globe are used as a reference. Fig. 1 shows the ratios of both satellite datasets averaged from 60°N-60°S to the corresponding ground-based time series. The differences exhibit a strong seasonal cycle within ±5%, and a slight positive drift of about +1.2% per decade for the GOME data with respect to ground data and +1.9% per decade for the TOMS data, respectively.

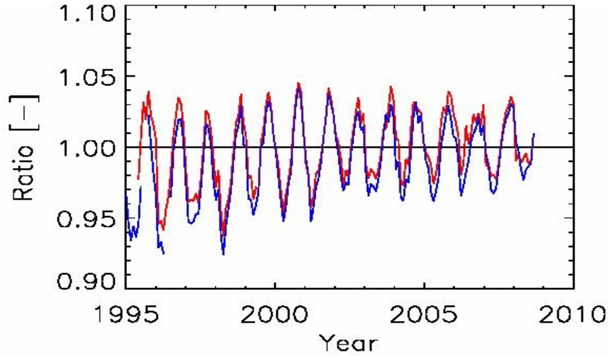

Figure 1: Ratio of GOME/SCIAMACHY/GOME-2 to Ground-based monthly ozone data averaged from 60°N-60°S in red, and ratio of TOMS/SBUV/OMI to Ground-based ozone data in blue.

It is important to notice that the size of the seasonality in the satellite to ground-based ratios in Fig. 1 is significant larger for this kind of monthly means comparisons in contrast to the direct comparison of collocated satellite and ground-based measurements.

1.1. Merged GOME total ozone

Monthly means for the single GOME, SCIAMACHY, and GOME-2 total ozone measurements are computed as area-weighted averages of daily composites on a grid of 0.33°x0.33° [3]. Furthermore global 1°x1° and 5°x5° gridded data, 1° zonal averages as well as the 60°N-60°S average have been computed. All data products use the GDP 4.x algorithm ([4], [2] and [7]). Near-real-time images and data from GOME-2 are available at http://wdc.dlr.de/sensors/gome2

In order to establish a homogeneous long-term time series the very stable GOME data record is used as a transfer standard, whereas SCIAMACHY and GOME-2 data are adjusted to GOME in periods of instrument overlap. The adjustment applied to SCIAMACHY is comprised of two parts: a basic latitudinal correction for each month of the year averaged from 2002 to 2009, and a time-dependent offset for each individual month, which accounts for the slight decreasing drift (<0.5% per year) found in the SCIAMACHY SGP v3.01 ozone columns compared to GOME [2].

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GOME-2 ozone columns are on average 2-3% lower than GOME values. As their overlap period is limited to 28 months from January 2007 to April 2009, the adjustment applied to GOME-2 is a latitude dependent correction factor for each single month. The final composition of the merged ozone product is listed in Table 1.

In case of instrument overlap periods, data are averaged weighted by the number of available observations. Due to the GOME tape recorder failure and the consequent loss of global coverage, no GOME data are used after June 2003.

Table 1: Composition of the merged GOME/SCIAMACHY/GOME-2 total ozone dataset.

Time period	Data / Instruments
06/1995 - 07/2002	GOME
08/2002 - 06/2003	GOME and SCIAMACHY
07/2003 - 12/2006	SCIAMACHY
01/2007 - 04/2009	SCIAMACHY and GOME-2

Fig. 2 shows the merged monthly 60°N-60°S average time series from June 1995 to April 2009. For comparison the original SCIAMACHY and GOME-2 data before the adjustment to GOME are also included. Apparent level shifts between the original data have been diminished in the merged time series.

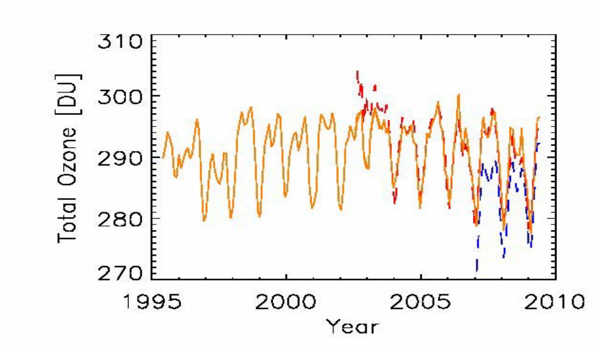

Figure 2: GOME, SCIAMACHY, and GOME-2 merged total ozone time series from 1995-2009 averaged from 60°N-60°S (orange). Red and blue dashed lines: corresponding SCIAMACHY and GOME-2 data before adjustment to GOME.

1.2. Merged TOMS total ozone

NASA's Merged Ozone Data sets (MOD) are monthly-mean zonal (5°) and gridded (5°x10°) average products constructed by merging individual TOMS, SBUV(/2), and OMI Version 8 satellite datasets. An external calibration adjustment has been applied to each satellite dataset in an effort to calibrate all the instruments to a common standard. The Earth Probe TOMS calibration from launch through summer 1999 is used as a reference standard, and all the other instruments are adjusted externally to match that calibration. Data are available through http://acdb-ext.gsfc.nasa.gov/Data_services/merged/mod_data.public.html. They almost continuously cover the time period from November 1978 to April 2009, see [5] for more details.

Fig. 3 shows a ratio of the merged TOMS/SBUV/OMI and the merged GOME/SCIAMACHY/GOME-2 datasets as function of latitude and time. There is an overall agreement in the order of 2% with the exception of the Polar Regions where the differences are larger.

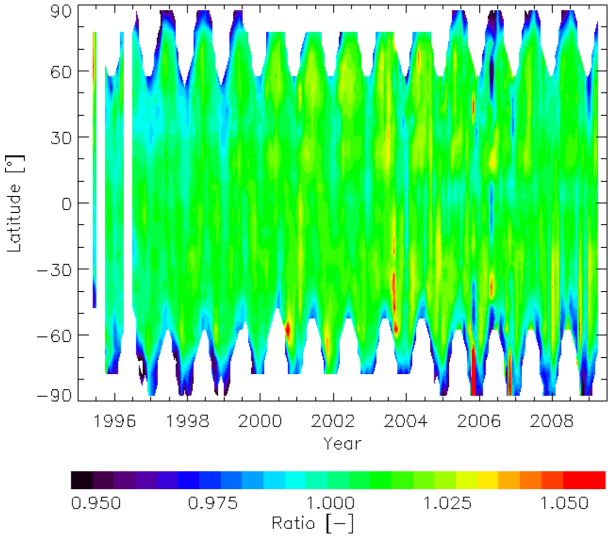

Figure 3: Ratio of the merged TOMS/SBUV/OMI and the merged GOME/SCIAMACHY/GOME-2 datasets. White regions indicate no data; there are not TOMS measurements in late 1995 and early 1996.

1.3. Ground-based measurements

For this study, archived total ozone measurements from about 70 Dobson and Brewer ground-stations were used as reference. Data are available through the World Ozone and Ultraviolet Radiation Data Center (WOUDC, http://www.woudc.org). This well-established network covers a wide geographical extent and has often been used for both validations of satellite data as well as trend studies.

The quality criteria for the selection of individual stations are described in detail in [1].

2. TREND ANALYSIS

A typical linear statistical model similar to that used in [8] describing observations of monthly mean total ozone data in the form

$$\Omega(t)=\mu+A(t)+T(t)+Q(t)+S(t)+N(t) \qquad (1)$$

was used in this study. Herein $\Omega(t)$ denotes total ozone, t is the number of months after June 1995, μ is the overall mean, $A(t)$ represents the seasonal cycle, $T(t)$ the linear long-term trend, $Q(t)$ the quasi-biennial oscillation (QBO), $S(t)$ the solar cycle, and $N(t)$ are the residuals (noise). The unknown coefficients of the model are identified by multi-linear regression on the total ozone observations using a least squares method.

For the unexplained portion of the data the noise $N(t)$ is assumed to be autoregressive of the order of 1; that is $N(t) = \phi\ N(t\text{-}1) + \varepsilon(t)$, where $\varepsilon(t)$ are independent, normally distributed random errors. A Cochrane-Orcutt transformation [6] is applied to the regression equation using an estimate of the auto-correlation coefficient ϕ with time lag of one month in order to ensure that the remaining residuals fulfil this assumption. The fit uncertainty σ is the variance of the noise $N(t)$. Sine and Cosine terms in $A(t)$, $Q(t)$, and $S(t)$ account for their seasonal dependence. The QBO signal is represented using winds at both 30 and 50 hPa. $S(t)$ is the solar flux measured at a wavelength of 10.7 cm. The starting point of our analysis is June 1995 which is very close to the expected turning point and beginning of recovery of total ozone. Therefore we decided to use at first a simple linear trend model instead of a piecewise linear trend. It is planned to replace this linear trend with the equivalent effective stratospheric chlorine time series (EESC).

Fig. 4 gives an example of fitting the merged GOME 60°N-60°S time series from June 1995 to April 2009. The estimated linear trend is 0.44% (±0.6%) per decade. The coefficient of multiple determination R^2 is equal to 0.963, indicating that the selected proxies represent about 96% of the variability in the ozone data. The auto-correlation coefficient with time lag of one month of the residual using the transformed model is 0.03, whereas it is 0.56 without transformation.

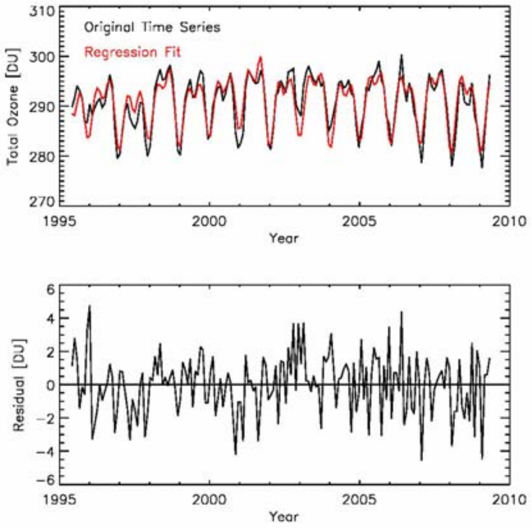

Figure 4: Example of fitting the merged GOME/SCIAMACHY/GOME-2 60°N-60°S time series (top panel) and the remaining residuals (bottom panel).

2.1. Latitudinal Trends

For the merged GOME ozone dataset 1° zonal averages have been calculated. Due to the limited coverage of ground data 5° belts were selected for them. Merged TOMS data are also available as 5° zonal means.

In Fig. 5 estimated latitudinal total ozone trends for the time period 1995 to 2009 are shown. The latitudinal behaviour of trends derived form GOME and TOMS is very similar. The agreement with ground data is good especially in the northern hemisphere. Significant trends, i.e.$|$trend$|$> 2σ-error, are obtained between 5°S and 30°N for both satellite datasets.

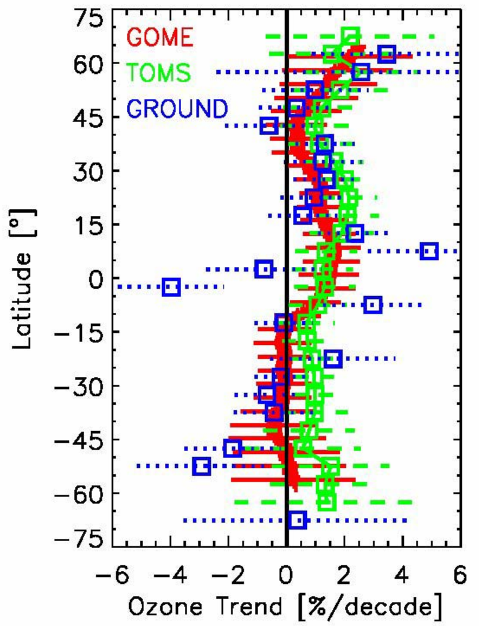

Figure 5: Estimated GOME (red), TOMS (green) and GROUND (blue) zonal ozone trends and 2σ-error.

2.2. Global Trends

Fig. 6 shows linear global (5°x5°) total ozone trends from June 1995 to April 2009 for the GOME/SCIAMACHY/GOME-2 and the TOMS/SBUV(/2)/OMI datasets, respectively. In general the patterns of both regressions are very similar. Significant positive trends appear in the tropics and in the northern hemisphere over Europe and Canada. The negative trend in the ocean region south from Africa is more marked in the merged GOME as in the merged TOMS results. In the same way the positive trends in the north part of South America, India and Indonesia are more prominent in the merged GOME and the ground-based results (not shown) than in the merged TOMS results.

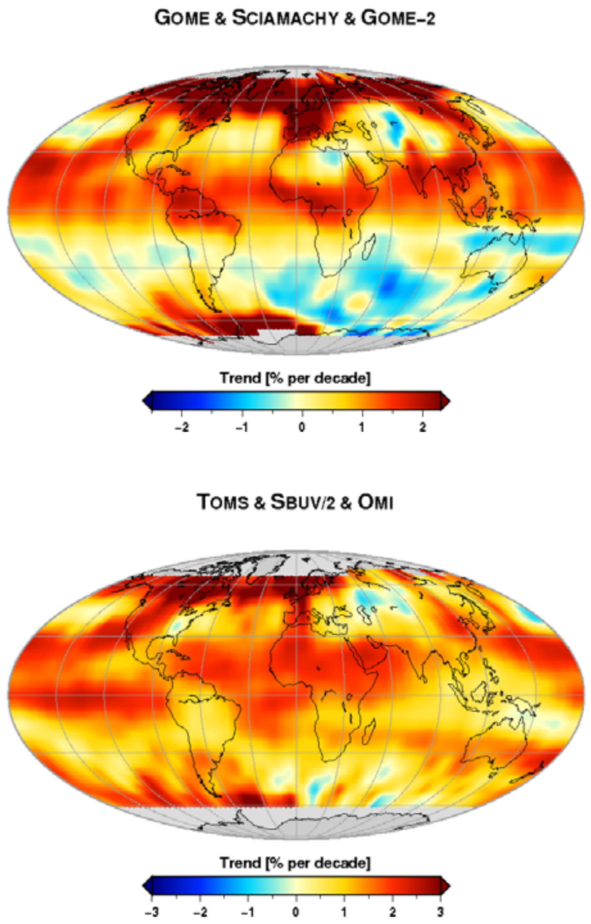

Figure 6: Global total ozone trend in % per decade for GOME/SCIAMACHY/GOME-2 (upper panel) and TOMS/SBUV/OMI (lower panel).

Fig. 7 shows the number of years required to detect a trend of 1% per decade in the merged GOME dataset following the approach of [6]. The number of required measurement years increases with increasing fit uncertainty (σ) and increasing autocorrelation in the noise term from (1).

The merged GOME dataset can already detect real trends at the level of 5% per decade from 60°N to 60°S with a 95% confidence level. The number of required measurement years increase considerable for detecting trends at the level of 1% per decade with a 95% confidence level. In the tropics 10 to around 20 years of GOME data are required, i.e. the merged GOME time series, which now completes 14 years, is already on the verge of it. In high latitudes more than 30 years of measurements are needed, whereas in the Polar Regions even more years of measurements are required due to the missing UV/VIS measurements during the polar night periods.

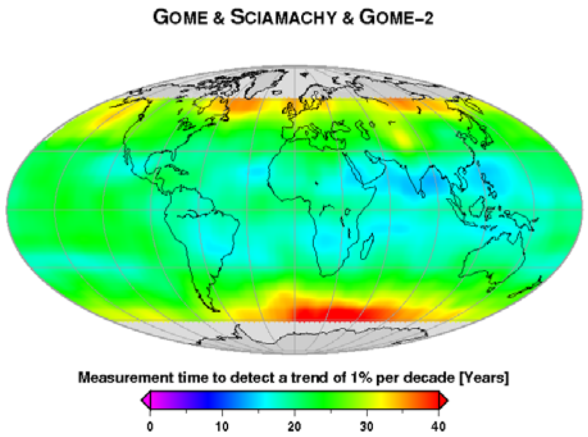

Figure 7: Number of years required to detect a trend of 1% per decade with a 95% confidence level using the merged GOME dataset.

3. SUMMARY AND OUTLOOK

This work presents for the first time a global total ozone trend analysis using a homogeneous self-consistent long-term ozone data record with fourteen years of data from GOME/SCIAMACHY/GOME-2. This merged dataset is free available from the following URL: http://wdc.dlr.de/data_products/TRACEGASES/merged_total_ozone.php

A global slightly positive trend (<1% per decade) in the total ozone since June 1995 from the merged GOME dataset was found, with marked positive and negative regional patterns. The trend agrees well with both an independent satellite dataset and ground-based measurements.

The statistical analysis shows that the amount of merged GOME data available already gives a 95% confidence level to detect a trend of the order of 1% per decade in the tropical region and a trend of the order of 5% from 60°N to 60°S. Additional years of measurements are needed to reach the same confidence level for high latitudes and even more for the Polar Regions.

It is planned to extend this work in the framework of the ESA Climate Change Initiative. At the same time DLR is looking forward for continuing the partnership with ESA and EUMETSAT for the generation of the operational products of the next European atmospheric composition sensors: GOME-2/Metop-B (start 2012) and Sentinel 5 precursor (start 2014).

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