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Global Monitoring of Atmospheric Trace Gases, Clouds and Aerosols from UV/vis/NIR Satellite Instruments: Currents Status and Near Future Perspectives

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Abstract. A new generation of UV / vis / near-IR satellite instruments like GOME (since 1995), SCIAMACHY (since 2002), OMI (since 2004), and GOME-2 (since 2006) allows to measure several important stratospheric and tropospheric trace gases like O_3, NO_2, $OClO$, $HCHO$, SO_2, BrO, and H_2O as well as clouds and aerosols from space. Because of its extended spectral range, the SCIAMACHY instrument also allows the retrieval of Greenhouse gases (CO_2, CH_4) and CO in the near IR. Almost all of the tropospheric trace gases are observed by these instruments for the first time. From satellite data it is possible to investigate the temporal and spatial variation. Also different sources can be characterised and quantified. The derived global distributions can serve as input and for the validation of atmospheric models. Here we give an overview on the current status of these new instruments and data products and their recent applications to various atmospheric and oceanic phenomena.

Introduction

In order to make reliable predictions of future changes of climate and air quality, usually numerical computer simulations are performed. These simulations are based on our current understanding of the physics and chemistry, as well as on the dynamical fields of the atmosphere and oceans. Also the interactions between the different parts of the system Earth, like atmosphere, ocean, cryosphere, etc. are considered. As output of these models typically 4-dimensional fields of constituent concentrations (e.g. air pollutants, greenhouse gases) and radiative properties are determined. To check the validity of the model simulations, it is important to compare these fields to measurements. For the atmosphere, a large variety of in-situ and remote sensing techniques can be used for the comparison, with specific advantages and disadvantages for each technique. Compared to other kinds of measurements, satellite observations have specific advantages. First, they provide global observations and allow e.g. to retrieve information from remote regions (often for the first time). Second, they typically yield integrated quantities, e.g. the vertically integrated trace gas concentration. Together with the first aspect, this capability ensures that satellite observations typically don't miss important information (e.g. from a specific location). Third, from satellite observations information on spatial patterns can be derived. In this way it is often possible to assign an observed phenomenon directly to a specific origin (e.g. enhanced trace gas concentrations above an industrialized area). Also, direct comparisons of observations made at different locations become possible. Fourth, typically satellite instruments are very stable and allow to determined trends on a global scale (e.g. the increase of pollutants or greenhouse gases). Major limitations of satellite observations are their relatively large measurement uncertainty, their coarse spatial resolution and their rare sampling.

Here we give an overview on the analysis of trace gas distributions, and aerosol and cloud properties from modern UV / vis / near-IR satellite instruments. We discuss the major processing steps, show images with the average global distributions and present selected case studies. Finally we give an outlook on future developments.

Instruments

The (Global Ozone Monitoring Experiment (GOME) is one of several instruments aboard the European research satellite ERS-2 [1], which was launched in 1995. It consists of a set of four spectrometers that simultaneously measure sunlight reflected from the Earth's atmosphere and from the ground in four spectral windows covering the wavelength range between 240 nm and 790 nm with moderate spectral resolution (0.2-0.4 nm full width at half maximum (FWHM)). The satellite operates in a nearly polar, Sun-synchronous orbit at an altitude of 780 km with a local equator crossing time at approximately 1030. While the satellite orbits in an almost north-south direction, the GOME instrument scans the surface in the perpendicular, east-west direction. During one sweep, three individual spectral scans are performed. The corresponding three ground pixels (a western, a center, and an eastern pixel) lie side by side, each covering an area of 320 km (east-west) by 40 km (north-south). The Earth's surface is totally covered within 3 days. In 2002 the SCanning Imaging Absorption SpectroMeter for Atmospheric ChartographY (SCIAMACHY) [2] was launched on board of ENVISAT. In addition to GOME it measures in a wider wavelength range (240 nm - 2380) including also the absorption features of several greenhouse gases (CO_2, CH_4, N_2O) and CO in the IR. It operates in different viewing modes (nadir, limb, occultation), which also allow to derive stratospheric trace gas profiles. Another advantage is that the ground pixel size for the nadir viewing mode was significantly reduced to 30 x 60 km^2 (in a special mode even to 15 x 30 km^2). Especially for the observation of tropospheric trace gases this is very important because of the strong spatial gradients occurring for such species. In addition, the Ozone Monitoring Instrument (OMI) was launched on AURA in 2004. Like GOME it operates only in nadir geometry. It has a reduced spectral range (270 and 500 nm), but a finer spatial resolution (up to 13x16km^2) and daily global coverage [3]. Recently, the first GOME-2 instrument (in total three instruments are scheduled) was launched on METOP in 2006. It is similar to the GOME-1 instrument, but with finer spatial resolution (40x80km^2) and almost daily global coverage [4].

Data analysis

From the raw satellite spectra the absorptions of the individual atmospheric trace gases are determined using differential optical absorption spectroscopy (DOAS) [5]. In brief, the measured spectra are modeled with a nonlinear fitting routine that suitably weights the known absorption spectra of atmospheric trace gases and a solar background spectrum, frequently called the solar Fraunhofer reference spectrum. Also, the influence of atmospheric Raman scattering (the so-called Ring effect) is considered [6]. Contributions of atmospheric broadband extinction processes (e.g., Rayleigh, and Mie scattering) are removed from the spectrum by fitting a polynomial of low order. In Fig. 1 the wavelength ranges are indicated where the different atmospheric trace gases are analyzed. For each species, spectral regions are selected where the most prominent differential absorption structures appear or/and the smallest spectral interferences with other species are expected. In Fig. 1 also the results of the spectral analysis are presented. The yellow lines indicate the absorption spectra of the respective trace gas scaled to the absorptions determined in the GOME spectrum (blue lines). From the inferred absorption, and the knowledge of the differential (narrowband) absorption cross section, the trace gas slant column density (SCD, the integrated trace gas concentration along the absorption path) is calculated.

For the interpretation of the obtained SCD, radiative transfer modeling (RTM) is performed. Typically the results of RTM are expressed as air mass factors (AMF), where AMF = SCD / VCD (with VCD the vertical column density, the vertically integrated trace gas concentration). In a rough, first approximation the AMF is given by the ratio of the path length of the sunlight through the atmosphere and the vertical path, i.e., AMF $\approx$ 1/cos(SZA) + 1/cos(AAO) with SZA the solar zenith angle and AAO the average angle of the observation. We calculate AMFs using the Monte Carlo RTM TRACY-2, which includes spherical geometry and multiple scattering [7,8]. The AMF mainly depends on the SZA, the atmospheric concentration profile of the measured species and the ground albedo.
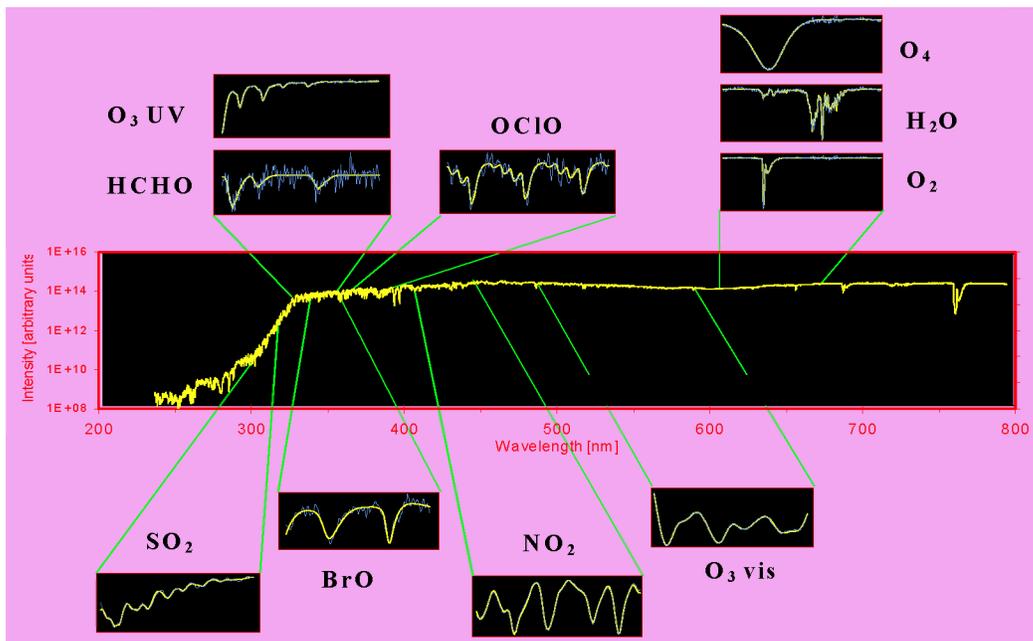
FIGURE 1. Selection of wavelength ranges for the spectral analysis of the different trace gases analyzed from GOME spectra. The thick lines indicate the absorption spectra of the trace gases scaled to the absorptions determined in the satellite spectrum (thin lines). In the near-IR (not shown) the absorptions of CH_4, CO_2, and CO can be analysed.
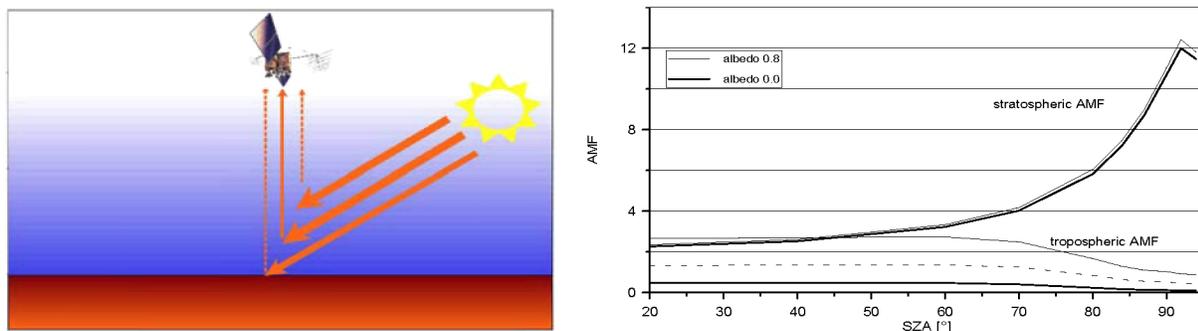

FIGURE 2. Left: viewing geometry for satellite observations in nadir mode. The received light is scattered by the atmosphere and reflected from the ground. Right: Influence of the ground albedo on the AMFs for trace gas profiles in the stratosphere (maximum concentration at 14 km) and the lower troposphere (constant concentration in the boundary layer between the surface and 1 km). In contrast to the stratospheric AMF, the tropospheric AMF depends strongly on the ground albedo. The dashed line shows the AMF which is appropriate for trace gas in the boundary layer. It is calculated assuming a ground albedo of 0.8 and a geometric cloud fraction of 0.5.

In Figure 2, examples of AMFs for stratospheric and tropospheric profiles are displayed. The AMF for the trace gases located in the stratosphere (AMF_{strat}) strongly increases toward high SZA; in contrast, the AMF for species in the lower troposphere (AMF_{trop}) shows only a weak SZA dependence. While for SZA $\leq 87°$ the AMF_{strat} can be calculated with high accuracy, the calculations for AMF_{trop} show large uncertainties due to several reasons:

1. Because of the high air pressure and high (and variable) aerosol concentration in the troposphere, the influence of multiple scattering is large compared to the stratosphere.

2. The influence of the ground albedo on the sensitivity (and accordingly the respective AMF) of the satellite observations to tropospheric species is strong compared to the stratosphere (see Figure 2). AMF_{trop} is small when

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the ground albedo is small (e.g., above the ocean) and large when the ground albedo is high (e.g., over snow and ice).

3. Clouds can shield absorbing species which are located below the cloud cover. This effect is in particular strong when the ground albedo is low (e.g., above the ocean).

Because of these uncertainties, the quantitative determination of tropospheric trace gases from satellite with high accuracy is only possible when precise information about the above mentioned parameters is available. This is in general not the case for a single observation. However, when satellite observations are spatially and temporally averaged the uncertainties decrease significantly.

Global mean maps

Several tropospheric trace gases like NO_2, HCHO, BrO, SO_2, H_2O, Glyoxal, CO, CH_4, CO_2 and IO are currently retrieved from satellite observations. Here we show some examples which illustrate the potential of these new data sets. In Fig. 3 the global distributions of tropospheric NO_2 and Formaldehyde (HCHO) are shown. NO_2 is a pollutant which affects human health and controls ozone chemistry. HCHO is an indicator for photochemical activity in the atmosphere. It is produced during the degradation of methane (and many other hydrocarbons). Large amounts of HCHO are also observed over regions of strong biomass burning.
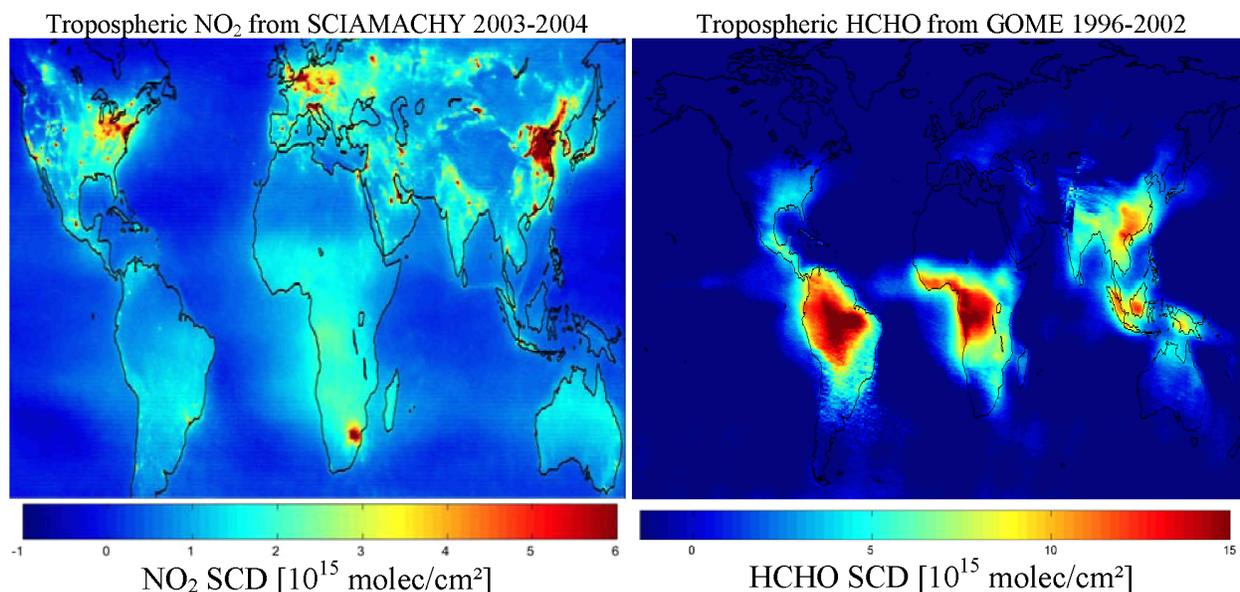

Tropospheric NO_2 from SCIAMACHY 2003-2004   Tropospheric HCHO from GOME 1996-2002

NO_2 SCD [10^{15} molec/cm²]   HCHO SCD [10^{15} molec/cm²]

FIGURE 3. Global distributions of tropospheric NO_2 and HCHO. The observed patterns indicate the locations of major sources.

Selected Applications

The information on the global distribution of atmospheric trace gases can be utilized in various ways. One important possibility is to compare the satellite results with spatial patterns derived from other sources; one example is shown in Fig. 4. The tropospheric NO_2 distribution is compared to the distribution of ship traffic. To make the spatial structures in the NO_2 observations more clear, a high pass filtering in latitudinal and longitudinal directions was applied. The NO_2 emissions caused by ship traffic are clearly visible in the satellite observations. Although the enhancements are small, they can be unambiguously assigned to the emissions of ships [9].
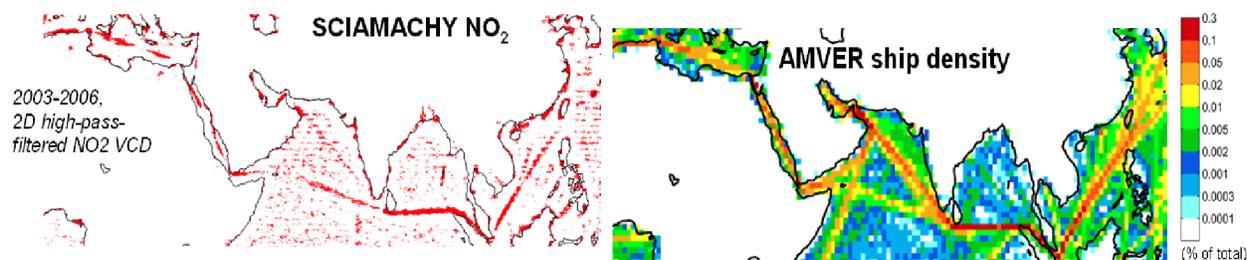
FIGURE 4. Tropospheric NO$_2$ distribution derived from satellite observations (left) and ship traffic density (right).

Another important possibility is to compare the satellite results to model simulations. In Fig. 5 the tropospheric NO$_2$ patterns for two consecutive days are compared to the respective results from an atmospheric transport model. From the good agreement between model results and satellite measurements, confidence can be gained in both the observed and modeled transport patterns. In this case, pollution from the US is transported to Europe within one day [10].
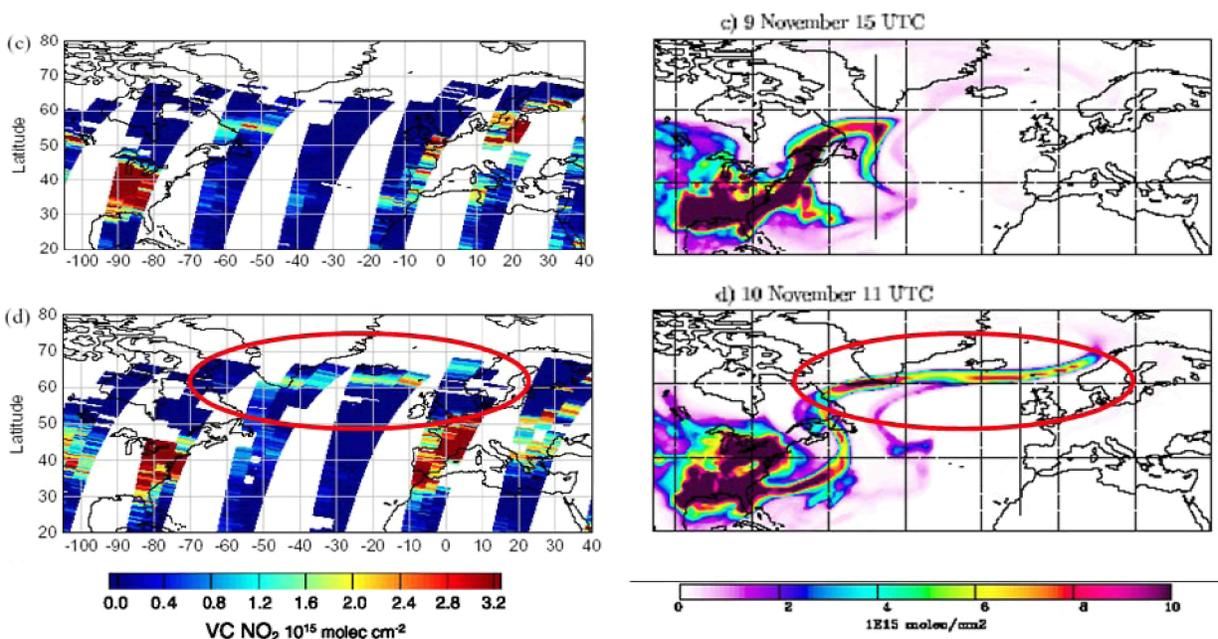

FIGURE 5. Comparison of satellite observations of NO$_2$ (left) and model results for two consecutive days. Atmospheric pollution from the US is transported to Europe within one day (red ellipse) [10].

Effects of clouds and aerosols

Clouds shield the underlying atmospheric layers; thus the retrieved tropospheric trace gas absorptions from satellite observations depend strongly on the properties of the cloud cover. Often, the precise knowledge of the cloud properties is the most limiting factor for the accurate retrieval of tropospheric trace gas products. Information about clouds can be derived from the satellite observations themselves, e.g. from measured radiance and the absorptions of atmospheric O$_2$ and its dimer (O$_4$). Since the atmospheric concentration of oxygen is nearly constant, variations in the measured absorptions are a direct indication of modifications of the radiative transport through the atmosphere (e.g. due to clouds or aerosols). In Fig. 6 it is shown that in the presence of clouds the absorptions of O$_2$ and O$_4$ are reduced. Also information on the aerosol load can be derived from the measured absorptions of O$_2$ and O$_4$.

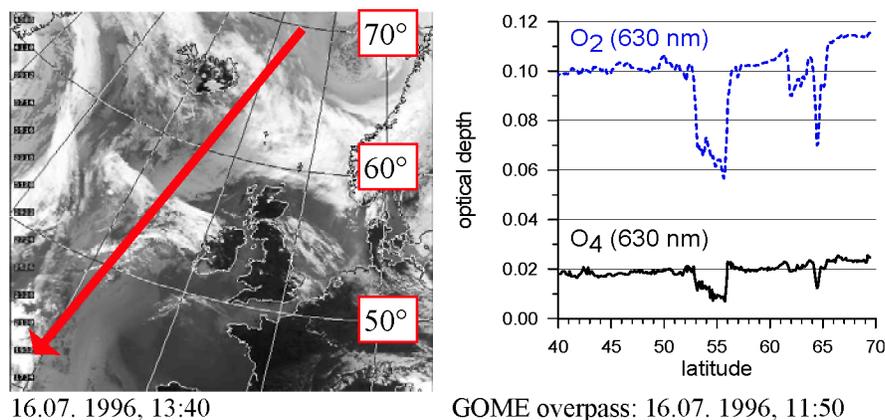16.07. 1996, 13:40   GOME overpass: 16.07. 1996, 11:50

FIGURE 6. Influence of clouds on the absorption of species which are mainly located in the troposphere like O_2 and the oxygen dimer O_4. Left: Satellite image of the GOME flight track. Right: Absorptions of O_2 and O_4 are significantly decreased when clouds are in the field of view. The images are obtained via the Dundee Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk/).

Conclusions and Outlook

We demonstrated that a variety of atmospheric trace gases can be retrieved from the spectra measured by UV / vis / near-IR satellite instruments. From these new instruments, it is possible to monitor and investigate several important atmospheric phenomena on a global scale (e.g. anthropogenic and natural emissions of pollutants and greenhouse gases). Because of the long operational time of GOME and its successors (since 1995), it is in particular possible to derive trends over a period of more than 12 years. Future improvements of the tropospheric data analyses will mainly address the improvement of the correction of the effects of clouds. For that purpose in particular the combined analysis of atmospheric O_2 and O_4 absorptions can be used.

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