Evidence from Satellite Data for Export phenomena

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1. Summary

The study investigates the potential of satellite observations of atmospheric trace gases for the investigation of export phenomena, in particular intercontinental transport. Atmospheric trace gases are measured by various satellite instruments in different wavelength ranges. Especially nadir viewing instruments operating in the UV/vis (and near IR) spectral range are sufficiently sensitive even for trace gases located in the troposphere (see e.g. Fishman et al., 1986). It was recently demonstrated that several trace gases located even in the planetary boundary layer (e.g. NO2, HCHO, SO2, BrO, H2O) can be measured by such instruments, like e.g. the Global Ozone Monitoring Experiment (GOME) aboard ERS-2 (ESA, 1995). The analysis of tropospheric trace gases from GOME is described in several publications, see e.g. Wagner and Platt (1998), Richter et al. (1998), Eisinger and Burrows (1998), Leue et al. (2001), Velders et al. (2001), Wagner et al. (2001), Richter and Burrows (2002). General description of tropospheric trace gas measurements by GOME can be found in Burrows et al. (2000), Wagner et al. (2002a). An overview on tropospheric satellite data is also given on the TROPOSAT homepage: http://troposat.iup.uni-heidelberg.de/.

On March, 1, 2002, the Scanning Imaging Absorption SpectroMeter for Atmospheric ChartographY (SCIAMACHY) was launched aboard ENVISAT (see e.g. Bovensmann et al., 1999). In addition to nadir observations it also performs measurements of the atmosphere in limb viewing geometry. Compared to GOME the SCIAMACHY measuring modes enable several important advantages for the measurement of tropospheric trace gases:

a) The spatial resolution is significantly better (typically 30x60km² and at best 30x15km² compared to 40x320km²).

b) From the combination of limb and nadir observations the tropospheric column density can be directly inferred for trace gases which are located both in the stratosphere and troposphere.

c) From the additional near IR channels important greenhouse gases like CH4, N2O and CO2 (also CO) can be retrieved.

In this project the general properties of satellite observations of tropospheric trace gases are discussed. The methodology is described in some detail for DOAS observations made by GOME and SCIAMACHY. In the following parts an overview is given on observations of several tropospheric trace gases by GOME. Examples for intercontinental transport are presented in case studies and from averaging global satellite data over several years. Finally the potential of satellite observations for the discrimination of different sources is highlighted.

2. General characteristics of satellite observations of atmospheric trace gases

Compared to observations made from ground, balloon or aircraft, satellite observations of atmospheric trace gases have several important advantages:

a) Satellites have nearly global coverage. Thus they allow e.g. measurements in remote regions. In addition, it is possible to measure and directly compare trace gases in different
regions of the world. Often it is also possible to discriminate between temporal and spatial variability of atmospheric trace gases.

b) Satellite instruments typically yield large data sets. Thus, extended statistical investigations can be performed.

c) Satellite instruments are nearly not affected by mechanical influences. Besides instrumental degradation they are thus usually very stable.

d) Because of their special operation conditions specific calibration measurements, e.g. the observation of direct sun light spectra can be performed.

In spite of these advantages it should be noted that they are also subject to systematic shortcomings (see also below). In particular they can not replace observations from other platforms. Best use of satellite measurements can be made in conjunction with observations from other platforms.

Important limitations of satellite observations of tropospheric trace gases are:

a) The spatial and temporal coverage is restricted. Global coverage for polar orbiting satellite instruments like GOME and SCIAMACHY is reached after 3 and 6 days, respectively. Polewards of about 60° full spatial coverage is already reached after 1 day for GOME and 2 days for SCIAMACHY. For possible future geostationary platforms (like GEOTROPE, see Burrows et al., 2002) the temporal coverage can be much better (about every 30 min) while the spatial coverage is limited to only a part of the whole globe.

b) Compared to imaging satellite instruments (like weather satellites) the spatial resolution is poor. The typical ground pixel size of GOME is 40x320 km², for SCIAMACHY it is 30x60 km². In a special mode, however, SCIAMACHY can have ground pixels of only 30x15 km².

c) Typically no altitude information on tropospheric trace gases is inferred from satellite observations. The standard satellite product is thus the tropospheric vertical column density, the vertically integrated trace gas concentration. However, some techniques allow to derive a limited amount of information on the vertical distribution, e.g. ‘cloud slicing’ (Ziemke et al., 1998) or the combination of observations in different wavelength ranges (Richter and Burrows, 2002).

d) Tropospheric trace gas observations from space have typically large uncertainties because of several reasons. First the influence of multiple scattering is relatively large, in particular also the influence of aerosols and the ground albedo. In addition, clouds strongly affect tropospheric observations from satellite instruments and contribute the dominant source of error for most single measurements (Wagner et al., 2002b).

3. DOAS analysis for GOME and SCIAMACHY

In this chapter the DOAS analysis is described for GOME observations. This analysis, however, can be directly transferred to the nadir observations of SCIAMACHY.

From the raw spectra monitored by GOME the absorptions of each of the UV/vis absorbing atmospheric trace gases is determined using differential optical absorption spectroscopy (DOAS) (Platt, 1994). In brief, the measured spectra are modelled with a non-linear fitting routine that suitably weights the known absorption spectra of atmospheric trace gases and a solar background spectrum. Also, the influence of atmospheric Raman scattering (the so-called Ring effect) is considered (Grainger and Ring, 1961; Solomon et al. 1987; Bussemer, 1993). Contributions of atmospheric broadband extinction processes (e.g., Rayleigh, and Mie scattering) are removed from the spectrum by fitting a polynomial. In Fig. 1 the wavelength ranges are indicated where the different atmospheric trace gases are analysed. 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 for different trace gases are presented (small plots). 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 absorption cross section, the trace gas slant column density (the integrated trace gas concentration along the absorption path) is calculated.

Figure 1: Selection of wavelength ranges for the spectral analysis of the different trace gases analysed from GOME spectra. The thick lines indicate the absorption spectra of the trace gases scaled to the absorptions determined in the GOME spectrum (thin lines).

Figure 2: Influence of the ground albedo on the sensitivity (expressed as AMF, see text) for trace gases located in the in the stratosphere and the lower troposphere (in the boundary layer). In contrast to the stratospheric AMF, the tropospheric AMF depends strongly on the ground albedo (see also Wagner et al., 2001).

The light which reaches the instrument is either reflected from the Earth’s surface or scattered back from the atmosphere. Therefore the determination of the vertical column density (VCD, the vertically integrated concentration) from the measured SCD requires radiative transport
modelling. The results of these calculations are usually expressed as air mass factors (AMF), where $\text{AMF} = \frac{\text{SCD}}{\text{VCD}}$. We calculate AMFs using a Monte Carlo RTM including spherical geometry and multiple scattering (Marquard et al., 2000). In Figure 2, examples of AMFs for stratospheric and tropospheric profiles are displayed.

4. Observations of export phenomena

In these chapter examples are given for the measurement of export phenomena from space.

4.1 Single episodes

The identification of single episodes of export phenomena is complicated by two major factors: the limited temporal sampling frequency and the influence of clouds. Especially in the case of extended cloud coverage tropospheric trace gases below the cloud layer are not visible. Thus it is important to monitor the appearance of clouds to estimate their possible impact on the tropospheric trace gas measurements. In cases of broken clouds it will even be possible to correct the cloud influence (see Wagner et al., 2002b).

![GOME tropospheric NO$_2$ vs Flexpart NO$_x$ tracer](image)

Fig. 3 Case study of transport of anthropogenic NO$_2$ in the easterly outflow of South Africa. In the left part tropospheric NO$_2$ VCDs derived from GOME observations are displayed. Grey parts of the GOME orbits indicate large cloud fractions shielding the atmosphere below. In the right part model simulations using the FLEXPART model are displayed (Stohl et al. 1998). Similar structures can be found in both data sets (see also Wenig et al. 2002).
To compensate for the limited sampling frequency satellite observations can be compared to model results. If the spatial and temporal patterns agree it can be concluded that both, the satellite observations and the model studies have identified export phenomena (see Figure 3). In some cases the signals of export phenomena in the satellite data are very strong. Then transport over large distances can be directly identified from satellite data (see Fig. 4).

Fig. 4 Three day composite of GOME SO₂ observations over Africa (5.-7. December 1996). The SO₂ plume from the eruption of the Nyamuragira Volcano is transported hundreds of kilometres in westerly directions (see also Eisinger et al., 1998).

4.2 General transport patterns in long time averages

Fig. 5 Six-years global average of the tropospheric NO₂ VCD measured by GOME (see also Beirle et al., this issue). Different sources of tropospheric NO₂ and also continental outflow patterns can be identified in this map.
For GOME observations already several years of data have been accumulated. Averaging of these large data sets permits to visualize transport patterns which might be too weak for a direct detection. In Figure 5 the 6-years average of the tropospheric NO$_2$ VCD is displayed (Beirle et al., 2002). In the mid latitudes transport in easterly direction can be identified for the outflow of several continents. In the Tropics transport patterns indicate transport in westerly direction.

5 Identification of different sources

5.1 Single episodes

Satellite observations allow to identify different sources of tropospheric trace gases. In many cases the sources can be directly identified for single episodes. This is in particular the case for the anthropogenic emission of NO$_2$ (see e.g. Fig. 3). Another example is shown in Fig. 6. Enhanced values of HCHO appear over Borneo during the heavy biomass burning in September 1997. High values were also found for tropospheric NO$_2$.

Fig. 6 Tropospheric NO$_2$ and HCHO measured by GOME on 27 September 1997 over Borneo. During that period of time heavy biomass burning took place.

5.2 Correlation studies

Fig. 7 Correlation of tropospheric NO$_2$ VCDs with satellite observations of the brightness of the night side of the earth (This correlation was investigated together with Franz Rohrer, FZ Jülich, Germany, personal communication). Low NO$_2$ VCDs only appear for ‘dark’ areas of the world; for bright areas always high tropospheric NO$_2$ VCDs are found.
In many cases different sources contribute simultaneously to the observed trace gas absorptions. From the correlation of tropospheric GOME observations with other data sets it is possible to discriminate different sources. In addition, correlation studies allow to quantify the strength of these sources. It was demonstrated by Beirle et al. (this issue) that especially satellite sensors are well suited for such correlation studies. One example of such a correlation is shown in Fig. 7. The light density observed from the night side of the earth was correlated to the tropospheric NO$_2$ data from GOME. High values of tropospheric NO$_2$ only appear for bright areas of the world (Franz Rohrer, FZ Jülich, Germany, personal communication).

5 Conclusion and outlook

Satellite observations have a great potential for the investigation of export phenomena. UV/vis nadir looking instruments (like GOME and SCIAMACHY), in particular, have the capability to measure several tropospheric trace gases like NO$_2$, BrO, SO$_2$, HCHO, H$_2$O, O$_2$, and O$_4$. The good spatial and temporal coverage of satellite observations allows to identify single episodes of long range transport. From the extended data sets of satellite instruments also general transport patterns, e.g. the outflow of tropospheric NO$_2$ from the continents can be visualised. A promising possibility is also the correlation of the trace gas observations from satellites with independent satellite observations of other parameters, like, e.g. fire counts or lightning frequency (see Beirle et al., 2002). This method allows to identify different sources and to quantify their strengths.

The SCIAMACHY instrument (launched on ENVISAT in March 2002) will continue the tropospheric trace gas measurements of GOME with improved quality. For SCIAMACHY the ground pixel size is much smaller compared to that of GOME. In addition, the combination of limb and nadir measurements allows to directly determined the tropospheric column. This will yield improved tropospheric data e.g. also for O$_3$ which is mainly located in the stratosphere. Furthermore, from the near IR channels of SCIAMACHY several important greenhouse gases like CO$_2$, N$_2$O and CH$_4$ can be derived.

References


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