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**Greenhouse gases
from satellite –
Part 1: CO₂**

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Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite – Part 1: Carbon dioxide

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Abstract

Carbon dioxide (CO₂) and methane (CH₄) are the two most important anthropogenic greenhouse gases. SCIAMACHY on ENVISAT is the first satellite instrument whose measurements are sensitive to concentration changes of the two gases at all altitude levels down to the Earth's surface where the source/sink signals are largest. We have processed three years (2003–2005) of SCIAMACHY near-infrared nadir measurements to simultaneously retrieve vertical columns of CO₂ (from the 1.58 μm absorption band), CH₄ (1.66 μm) and oxygen (O₂ A-band at 0.76 μm) using the scientific retrieval algorithm WFM-DOAS. We show that the latest version of WFM-DOAS, version 1.0, which is used for this study, has been significantly improved with respect to its accuracy compared to the previous versions while essentially maintaining its high processing speed (~1 minute per orbit, corresponding to ~6000 single measurements, and per gas on a standard PC). The greenhouse gas columns are converted to dry air column-averaged mole fractions, denoted XCO₂ (in ppm) and XCH₄ (in ppb), by dividing the greenhouse gas columns by simultaneously retrieved dry air columns. For XCO₂ dry air columns are obtained from the retrieved O₂ columns. For XCH₄ dry air columns are obtained from the retrieved CO₂ columns because of better cancellation of light path related errors compared to using O₂ columns retrieved from the spectrally distant O₂ A-band. Here we focus on a discussion of the XCO₂ data set. The XCH₄ data set is discussed in a separate paper (Part 2). In order to assess the quality of the retrieved XCO₂ we present comparisons with Fourier Transform Spectroscopy (FTS) XCO₂ measurements at two northern hemispheric mid-latitude ground stations. To assess the quality globally, we present detailed comparisons with global XCO₂ fields obtained from NOAA's CO₂ assimilation system CarbonTracker. For the Northern Hemisphere we find good agreement with the reference data for the CO₂ seasonal cycle and the CO₂ annual increase. For the Southern Hemisphere, where significantly less data are available for averaging compared to the Northern Hemisphere, the CO₂ annual increase is also in good agreement with CarbonTracker but

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the amplitude and phase of the seasonal cycle show systematic differences up to a few ppm arising partially from the O₂ normalization. The retrieved XCO₂ regional pattern at monthly resolution over various regions show clear correlations with CarbonTracker but also significant differences. Typically the retrieved variability is about 4 ppm (1% of 380 ppm) higher but depending on time and location differences can reach or even exceed 8 ppm. Based on the error analysis and on the comparison with the reference data we conclude that the XCO₂ data set can be characterized by a single measurement retrieval precision (random error) of 1–2%, a systematic low bias of about 1.5%, and by a relative accuracy of about 1–2% for monthly averages at a spatial resolution of about 7° × 7°. When averaging the SCIAMACHY XCO₂ over all three years we find reasonable correlation with EDGAR anthropogenic CO₂ emissions for Germany, The Netherlands and Belgium indicating that regionally elevated CO₂ arising from regional anthropogenic CO₂ emissions can be detected from space.

1 Introduction

The atmospheric greenhouse gas carbon dioxide (CO₂) has increased significantly since pre-industrial times primarily as a result of fossil fuel combustion, land use change, cement production, and biomass burning, thus perturbing the natural global carbon cycle. Increasing CO₂ is predicted to result in a warmer climate with adverse consequences, such as rising sea levels and an increase of extreme weather conditions (IPCC, 2001, 2007). The reliable prediction of future atmospheric CO₂ levels and the associated global climate change requires an adequate understanding of the CO₂ sources and sinks. Unfortunately, this understanding has significant gaps and uncertainties are large (see, e.g., Stephens et al., 2007).

The current knowledge of the carbon dioxide surface fluxes is limited for example by the sparseness of the ground-based network with a lack of high-frequency surface observations in continental regions particularly outside North America and Europe. Theoretical studies have shown that satellite measurements of CO₂ in combination with

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models have the potential to significantly reduce CO₂ surface flux uncertainties (Rayner and O'Brien, 2001; Houweling et al., 2004). Existing satellite instruments whose measurements are sensitive to atmospheric CO₂ either measure radiances in the thermal infrared (TIR) spectral region such as HIRS (Chédin et al., 2002, 2003) and AIRS (Engelen et al., 2004; Engelen and McNally, 2005; Aumann et al., 2005; Strow et al., 2006) or SCIAMACHY in the near-infrared (NIR) / short wave infrared (SWIR) spectral region (Buchwitz et al., 2005a,b, 2006a, 2007b; Houweling et al., 2005; Bösch et al., 2006; Barkley et al., 2006a,b,c, 2007). Note that in this paper NIR and SWIR are commonly referred to as NIR. Whereas the TIR nadir measurements are primarily sensitive to middle to upper tropospheric CO₂, the NIR nadir measurements are sensitive to all altitude levels, including the boundary layer, which permits the retrieval of CO₂ total columns. High sensitivity to CO₂ concentration variations near the Earth's surface is important in order to get information on regional CO₂ sources and sinks. SCIAMACHY is the first and currently only satellite instrument which measures reflected solar radiation in the NIR spectral region covering important absorption bands of CO₂ (as well as CH₄ and O₂). For the near future other satellite missions are planned, most notably OCO (Crisp et al., 2004) and GOSAT (Hamazaki et al., 2004), which will also perform nadir observations in the NIR spectral region to retrieve CO₂.

As topographic features and surface pressure changes impact on the CO₂ total column, a more useful quantity for inverse modeling is the column-averaged dry air mole fraction of CO₂, denoted XCO₂, being defined as the total column of carbon dioxide divided by the dry air column. Dry air columns can be estimated by the simultaneous measurement of molecular oxygen (O₂) which is a well mixed gas with accurately known mole fraction exhibiting negligible (relative) variability. As CO₂ is a long-lived gas, the amount of the increase or decrease of its column-averaged mole fraction, as a result of a source or sink, is determined primarily by the strength and the spatial size of the source or sink and atmospheric transport. Although point sources such as the plumes from chimneys have large mole fractions locally, at the grid sizes of typical models or at the spatial resolution of the SCIAMACHY nadir measurements, sources and

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sinks only result in small changes of the column-averaged mole fractions on top of a large background. In order to determine such changes well, the resultant requirements on the accuracy and precision of the measurements of the column-averaged dry air mole fractions from space are demanding, being of the order of 1% or better (Rayner and O'Brien, 2001; Houweling et al., 2004; Miller et al., 2007; Chevallier et al., 2007).

Inverse modeling to obtain surface fluxes of carbon dioxide globally using the highly precise and accurate surface observations mostly based on weekly sampling relies on various assumptions (e.g., assumed flux pattern and uncertainties) and is currently typically restricted to large spatial scales (continents, ocean basins) due to the sparseness of the surface network (Bousquet et al., 1999; Gurney et al., 2002; Rödenbeck et al., 2003; Patra et al., 2006). In addition, attempts have been made for selected regions to better constrain the regional fluxes using continuous high-frequency CO₂ in-situ observations (Derwent et al., 2002; Peylin et al., 2005). As pointed out by Peylin et al. (2005), these regional results also depend critically on several assumptions used such as required smoothness, initial conditions, and the global flux field. As described above, inverse modeling of the CO₂ sources and sinks using satellite derived CO₂ columns has the potential to improve this situation but until now has not been undertaken due to lack of satellite data with sufficient quality.

In this manuscript, the first multi-year global dry air column-averaged CO₂ data set from SCIAMACHY is presented and discussed. A short first discussion of this data set has already been given in Buchwitz et al. (2007b) focussing on northern hemispheric large scale CO₂ features such as the seasonal cycle and the annual increase. The retrieval technique, called Weighting Function Modified DOAS, WFM-DOAS, developed at the University of Bremen for the retrieval of trace gases from SCIAMACHY has been described elsewhere (Buchwitz et al., 2000b; Buchwitz and Burrows, 2004; Buchwitz et al., 2005a,b). Other groups have developed somewhat different approaches to retrieve XCO₂ or CO₂ columns from SCIAMACHY. For example the column-averaged mole fractions retrieved using the computationally much more expensive Full Spectral Initiation WFM-DOAS (FSI/WFM-DOAS) algorithm (Barkley et al., 2006a,b,c, 2007) are

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obtained by normalizing the retrieved CO₂ column with surface pressure from meteorological analysis and not, as done here, by normalizing with simultaneously measured O₂. Houweling et al. (2005), using another algorithm for the retrieval of CO₂ column amounts from SCIAMACHY data, have identified problems due to aerosols especially when there are strong desert dust storms. Here we show that normalizing with measured O₂ reduces dust storm aerosol related errors. On the other hand we also show that normalizing with measured O₂ is not unproblematic under all conditions because of the different sensitivity of the radiances in the spectral regions used for CO₂ and O₂ column retrieval.

This manuscript is organized as follows: In Sect. 2 the SCIAMACHY instrument and its measurement principle are introduced and explained. This is followed by a description of the WFM-DOAS retrieval algorithm in Sect. 3 and an error analysis in Sect. 4. The new SCIAMACHY multi-year carbon dioxide data set is discussed in Sect. 5. Conclusions are given in Sect. 6.

2 The SCIAMACHY instrument

SCIAMACHY, which is a multi-national (Germany, The Netherlands, Belgium) contribution to the European environmental satellite ENVISAT, is a grating spectrometer that measures reflected, backscattered and transmitted solar radiation upwelling from the top of the atmosphere (Burrows et al., 1990; Burrows and Chance, 1991; Burrows et al., 1995; Bovensmann et al., 1999). The spectral region from 214 nm to 1750 nm is measured contiguously in six channels, and there are two additional channels covering the regions 1940–2040 and 2265–2380 nm (see Fig. 1). Each spectral channel comprises a grating focusing optics and a 1024 element monolithic diode array of the appropriate material. In addition, SCIAMACHY has 7 broad band channels, the Polarization Monitoring Devices (PMD), which monitor the upwelling radiation polarized with respect to the instrument plane at high spatial resolution providing sub-pixel information used in this study to identify cloud contaminated ground pixels.

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ENVISAT was launched into a sun synchronous orbit in descending node having an equator crossing time of 10:00 a.m. local time. During every orbit calibration measurements are made during the eclipse, followed by a solar occultation and limb atmospheric measurement. On the Earth's day side SCIAMACHY performs alternate nadir and limb observations. These measurements can be inverted to obtain a large number of atmospheric data products (Bovensmann et al., 1999). Of relevance to this study are the column amounts of CO₂ and O₂. As a result of SCIAMACHY's observation of greenhouse gas overtone absorptions in the near-infrared/short wave infrared (NIR/SWIR) solar backscattered spectrum, SCIAMACHY is the first satellite instrument that yields the vertical columns of CO₂ with high sensitivity down to the Earth's surface (Buchwitz et al., 2005a). As the integration time for the detectors is optimized around an orbit, the horizontal resolution of the nadir measurements depends on orbital position and spectral interval, but is typically 60 km across track times 30 km along track for the spectral fitting windows used in this study.

Overall, the in-flight optical performance of SCIAMACHY is very similar to that predicted from the pre-flight on ground characterization and calibration activities. One exception is a time dependent optical throughput variation in the SCIAMACHY NIR/SWIR channel 7, which has many resolved CO₂ absorption features, and channel 8, which has many CH₄ absorption features. This results from the in-flight deposition of ice on the detectors. As ice absorbs and scatters at these wavelengths this adversely affects the trace gas retrieval by reducing the signal to noise and changing the instrument slit function (Gloude-mans et al., 2005; Buchwitz et al., 2005b). As shown in Fig. 1, the WFM-DOAS version 1.0 results presented in this manuscript have been derived using CO₂ absorption features in channel 6 (1000–1750 nm) and O₂ A-band absorption in channel 4 (605–805 nm), which are not affected by an ice-layer, as their detectors operate at higher temperatures.

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3 WFM-DOAS retrieval algorithm

The retrieval of a long-lived and therefore relatively well-mixed gas such as carbon dioxide is challenging as only the small variations on top of a large background yield information on their surface sources and sinks. The retrieval algorithm has therefore to be accurate and, in addition, sufficiently fast to process the large amounts of data produced by SCIAMACHY. At the University of Bremen the Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) retrieval technique (Buchwitz et al., 2000b) has been developed for the retrieval of trace gases and optimized for the retrieval of CO₂, CH₄ and O₂. The results for methane are discussed in Schneising et al. (2008) (Part 2). The algorithm has been described in detail elsewhere (Buchwitz et al., 2000b; Buchwitz and Burrows, 2004; Buchwitz et al., 2005a,b). We therefore focus on a discussion of the main differences between the current version 1.0, which has been used to generate the data set discussed in this manuscript, and the previous version 0.4 (Buchwitz et al., 2005a,b; Dils et al., 2006a; Warneke et al., 2005).

3.1 Retrieval of vertical columns

WFM-DOAS is a least-squares method based on scaling (or shifting) pre-selected atmospheric vertical profiles. The fit parameters for the trace gases yield directly the desired vertical columns. The logarithm of a linearized radiative transfer model plus a low-order polynomial P is fitted to the logarithm of the ratio of the measured nadir radiance and solar irradiance spectrum, i.e., the observed sun-normalized radiance I^{obs} . The least-squares WFM-DOAS equation can be written as follows (the fit parameter vectors or vector components are indicated by a hat):

$$\sum_{i=1}^m \left(\ln I_i^{obs} - \ln I_i^{mod}(\hat{\mathbf{V}}, \hat{\mathbf{a}}) \right)^2 \equiv \|\mathbf{RES}\|^2 \rightarrow \min. \quad (1)$$

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where the linearized radiative transfer model is given by

$$\ln I_i^{\text{mod}}(\hat{\mathbf{V}}, \hat{\mathbf{a}}) = \ln I_i^{\text{mod}}(\bar{\mathbf{V}}) + \sum_{j=1}^J \frac{\partial \ln I_i^{\text{mod}}}{\partial V_j} \bigg|_{\bar{V}_j} \times (\hat{V}_j - \bar{V}_j) + P_i(\hat{\mathbf{a}}). \quad (2)$$

Index i refers to the center wavelength λ_i of detector pixel number i . The components of vectors \mathbf{V} , denoted V_j , are the vertical columns of all trace gases which have absorption lines in the selected spectral fitting window (interfering gas for the CO_2 fit is H_2O ; for the CH_4 fit interfering gases are H_2O and CO_2). The fit parameters are the desired trace gas vertical columns \hat{V}_j and the polynomial coefficients which are the components of vector $\hat{\mathbf{a}}$. An additional fit parameter also used (but for simplicity omitted in the equations given here) is the shift (in Kelvin) of a pre-selected temperature profile. This fit parameter has been added in order to take the temperature dependence of the trace gas absorption cross-sections into account. The fit parameter values are determined by minimising (in a linear least-squares sense) the difference between observation ($\ln I_i^{\text{obs}}$) and WFM-DOAS model ($\ln I_i^{\text{mod}}$), i.e. the “length” of fit residuum vector **RES** (with components RES_j) for all spectral points λ_i simultaneously. A derivative with respect to a vertical column refers to the change of the top-of-atmosphere radiance caused by a change (here: scaling) of a pre-selected trace gas vertical profile. The WFM-DOAS reference spectra are the logarithm of the sun-normalized radiance and its derivatives. They are computed with a radiative transfer model (Buchwitz et al., 2000a) for assumed (e.g. climatological) “mean” columns $\bar{\mathbf{V}}$. Multiple scattering is fully taken into account. The least-squares problem can also be expressed in the following vector/matrix notation: Minimize $\|\mathbf{y} - \mathbf{A}\mathbf{x}\|^2$ with respect to \mathbf{x} . The solution is $\hat{\mathbf{x}} = \mathbf{C}_x \mathbf{A}^T \mathbf{y}$ where $\mathbf{C}_x \equiv (\mathbf{A}^T \mathbf{A})^{-1}$ is the covariance matrix of solution $\hat{\mathbf{x}}$. The errors of the retrieved columns are estimated as follows (Press et al., 1992): $\sigma_{\hat{V}_j} = \sqrt{(\mathbf{C}_x)_{jj} \times \sum_i \text{RES}_i^2 / (m-n)}$, where $(\mathbf{C}_x)_{jj}$ is the j -th diagonal element of the covariance matrix, m is the number of

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spectral points in the fitting window and n is the number of linear fit parameters.

In order to avoid time-consuming on-line radiative transfer simulations, a fast look-up table scheme has been implemented. The pre-computed spectral radiances and their derivatives (e.g., with respect to trace gas concentration and temperature profile changes) depend on solar zenith angle, surface elevation (pressure), surface albedo, and water vapour amount (to consider possible non-linearities caused by the high variability of atmospheric water vapour). For carbon dioxide a single (constant) vertical profile is used for the retrieval to avoid that the measurements are influenced by variations artificially introduced by the retrieval method. These profiles (CO₂ mixing ratio, temperature, pressure) along with the vertical column averaging kernels, can be obtained from the WFM-DOAS web site http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/index.html. The CO₂ columns are retrieved using a small spectral fitting window in the near infrared (1558–1594 nm) located in SCIAMACHY channel 6, whereas oxygen, retrieved in order to derive the column-averaged CO₂ dry air mole fraction, is retrieved from a spectrally distant fitting window (755–775 nm, O₂ A-band) in SCIAMACHY channel 4. As an example, Fig. 2 shows the year 2003 average of the total columns of both gases (for a detailed discussion see Sect. 5).

The main differences between the previous version, version 0.4, and the new version, version 1.0, are the following:

(i) *Better consideration of albedo variability*: The surface albedo is specifically retrieved in each fitting window separately to consider its wavelength dependence in combination with an extended look-up table. The wavelength dependent surface albedo retrieval is based on comparing the measured sun-normalized radiance at selected wavelengths, in a transparent region of each fitting window where no significant gaseous or particulate absorptions occur, to pre-calculated radiances for different surface albedos. The retrieved surface albedo is used to account for the dependence of the top-of-atmosphere radiance on the surface albedo. In comparison, for computational simplicity, the previous WFM-DOAS versions used a constant wavelength independent surface albedo of 0.1. The extended look-up table includes surface albedos of 0.03,

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0.1, and 0.3 and an interpolation/extrapolation scheme is used to obtain the radiance and its derivatives for the retrieved surface albedo in each fitting window.

(ii) *Better consideration of surface elevation changes*: An extended look-up table scheme for surface elevation (pressure) has been implemented. The previous versions of WFM-DOAS used pre-calculated radiances and derivatives for surface elevations of 0 km, 1 km, 2 km, and 3 km in combination with a simple next neighbour approach. Now an extended data base covering also an altitude of 4 km is used in combination with an interpolation/extrapolation scheme to determine the radiance and its derivatives appropriate for the average surface elevation (pressure) of each ground scene. This significantly reduces the associated error of the retrieved columns (as discussed in detail below) which could be as large as a few percent in version 0.4 (Buchwitz et al., 2005a).

(iii) *Improved spectroscopy*: Update of the spectroscopic data to HITRAN 2004 (Rothman et al., 2005). The previous version was based on the line parameters for CO₂, O₂, and H₂O described in HITRAN 2000/2001 (Rothman et al., 2003).

(iv) *Improved calibration*: Usage of newly calibrated Level 1-Files (spectra) version 5. The SCIAMACHY Level 1 product is a geophysical product, describing the measured spectral radiance in units of photons/s/cm²/nm/steradian as a function of wavelength in units of nanometers. Our previous versions data products were based on the Level 1 version 4 data product. One significant error had been identified in the previous WFM-DOAS data product due to calibration problems of the version 4 spectra (Buchwitz et al., 2006a): systematically underestimated CO₂ columns which have been corrected to first order by scaling with the constant factor 1.27. Using the new Level 1 product this source of error is now negligible.

Another problem of XCO₂ v0.4 were systematically overestimated O₂ columns which have been corrected by scaling with the constant factor 0.85. The scaling factors for the CO₂ and O₂ columns used in the previous WFM-DOAS version 0.4 XCO₂ data product were chosen such that the CO₂ and O₂ columns were within experimental error close to their expected value of about 8×10^{21} molecules/cm² and 4.5×10^{24} molecules/cm²,

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respectively, for cloud-free scenes with a surface elevation corresponding to sea level. The need for an O₂ column scaling factor was removed by the improved treatment of surface albedo in WFM-DOAS version 1.0. In the previous version 0.4 a constant albedo of 0.1 was assumed and a surface spectral reflectance weighting function (derivative) was included for the O₂ column fit to minimize errors related to the variability of the surface spectral reflectance. The new approach removes the need for a weighting function for surface albedo in WFMdV1.0. The new version WFM-DOAS 1.0 yields the expected values for the CO₂ and O₂ columns without scaling.

3.2 Computation of column-averaged CO₂ dry air mole fractions

For carbon dioxide we derive column-averaged dry air mole fractions by normalizing the CO₂ columns with the simultaneously retrieved oxygen columns retrieved from the O₂ A-band. Oxygen is an accurate proxy for the air column because its mole fraction is well known and has negligibly small variations. The column-averaged mole fraction XCO₂ is computed as follows:

$$XCO_2 = \frac{CO_2^{col}}{(O_2^{col}/O_2^{mf})}, \quad (3)$$

where CO₂^{col} is the retrieved absolute CO₂ column (in molecules/cm²), O₂^{col} is the retrieved absolute O₂ column (in molecules/cm²), and O₂^{mf} is the assumed (column-averaged) mole fraction of O₂ used to convert the O₂ column into a corresponding dry air column and is equal to 0.2095. The resulting XCO₂ for the time period 2003–2005 is shown in Fig. 3 and will be discussed in Sect. 5.

3.3 Quality flags

In order to separate out ground scenes affected by clouds or poor spectral fits, quality flags marking successful measurements are set for each single measurement (i.e., for each observed ground scene).

For the column-averaged dry air mole fraction of carbon dioxide, measurements satisfying the following criteria are classified as being good by the WFM-DOAS retrieval and are subsequently used for the analysis described in this manuscript:

- The root-mean-square (RMS) of the fit residuum (relative difference between measurement and model after the fit) in the CO₂ fitting window has to be less than 0.25%.
- The RMS of the fit residuum in the O₂ fitting window has to be less than 2%.
- The CO₂ column fit error has to be less than 2.5%.
- The observed scene has to be nearly cloud free. Cloud contaminated ground scenes are identified using a threshold algorithm based on sub-pixel information provided by the SCIAMACHY Polarization Measurement Device (PMD) channel 1 detecting enhanced backscatter in the UV as described in [Buchwitz et al. \(2005a\)](#). In addition it is required that the retrieved O₂ column has to be larger than 90% of the assumed a-priori O₂ column (determined from surface elevation and the known mixing ratio of O₂).
- The SZA has to be less than 75°.
- The ground pixel must be over land (as the signal-to-noise ratio is typically significantly worse over water).
- The ground pixel must be a forward scan pixel (as the horizontal resolution of the backward scan pixel is four times larger (typically 240 km across track compared to 60 km for the forward scan)).
- The surface elevation has to be less than 5 km as higher altitudes are not covered by the current look-up table.

In addition, we filter for strong aerosol contamination as will be described in the next section.

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3.4 Aerosol filtering

Unaccounted variability of aerosols and clouds (including cirrus) in the retrieval is an important error source for CO₂ measurements from space (Tolton and Plouffe, 2001; O'Brien and Rayner, 2002; Kuang et al., 2002; Dufour and Bréon, 2003; Buchwitz and Burrows, 2004; Buchwitz et al., 2005a; Christi and Stephens, 2004; Mao and Kawa, 2004; Houweling et al., 2005; van Diedenhoven et al., 2005; Barkley et al., 2006a; Aben et al., 2006; Bril et al., 2007) as aerosols are highly variable and their optical properties (e.g., vertical profiles of phase function, extinction and scattering coefficients) are not known for each scene observed from satellite. This results in aerosol and clouds related errors which may be difficult to quantify. Figure 4 illustrates that unrealistically enhanced values appearing in the retrieved CO₂ mole fraction are correlated with enhanced levels of absorbing aerosols as retrieved by Earth Probe/TOMS (Herman et al., 1997) obtained from <http://toms.gsfc.nasa.gov/>. Aerosol types detected by the TOMS AAI include desert dust, smoke and volcanic ash located at least 2 km above the surface. During June 2003 the Absorbing Aerosol Index (AAI) is high over the Sahara due to desert dust storms. During this month the SCIAMACHY carbon dioxide data product also shows high values and good correlation with the aerosol index. During November AAI is low and the SCIAMACHY XCO₂ is not enhanced. This comparison shows that the retrieved carbon dioxide mole fraction can exhibit large (few percent) errors in case of strong desert dust storms. To remove aerosol contaminated retrieved XCO₂ for cases of high aerosol load, primarily over deserts (mainly Sahara), we apply an additional quality criterion for the global analysis of XCO₂ by rejecting ground scenes where the TOMS aerosol index is greater than a specific threshold. Figure 5 illustrates the AAI filtering.

In this context it is interesting to investigate whether the effect of overestimated CO₂ mole fractions in case of strong desert dust storms is dominated by errors of the CO₂ or the O₂ column. Figure 6 shows the XCO₂ data product over the Sahara obtained using the simultaneously retrieved O₂ column compared to that derived using model

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O₂ columns computed from surface pressure obtained from meteorological analysis:

$$O_2(\text{mod}) = \frac{p(\text{mod})}{1013\text{hPa}} \cdot 4.51 \cdot 10^{24} \frac{\text{molec}}{\text{cm}^2} \quad (4)$$

Assuming that the computed oxygen column obtained from meteorological (ECMWF) surface pressure is accurate, it can be concluded that the enhanced CO₂/O₂(mod) ratio over the Sahara must be due to an (at least relative to the surrounding areas) overestimated CO₂ column, which is consistent with the findings of [Houweling et al. \(2005\)](#) who showed by simulated retrievals that aerosol-induced path length enhancements can explain unrealistically enhanced carbon dioxide columns in the presence of desert dust.

Figure 6 additionally shows that the CO₂ column error cancels partially when computing the ratio with the measured O₂ columns. Therefore it can be concluded that aerosols due to strong desert dust storms are causing an overestimation of both the CO₂ and O₂ columns but affecting CO₂ to a greater extent so that the errors do not cancel completely in XCO₂. As can be seen, the CO₂ field is smoothest (and probably most realistic) if the aerosol filter is applied and if the retrieved CO₂ is normalized using the retrieved O₂ columns due to better cancellation of errors when the retrieved O₂ is used to compute XCO₂. We therefore conclude that the XCO₂ shown in the bottom left panel is the most accurate of the four XCO₂ data sets shown here.

As WFM-DOAS v1.0 uses a single constant aerosol scenario and aerosol variability is only accounted for to first order by the inclusion of a low order polynomial in the WFM-DOAS fit, this behavior is not unexpected ([Buchwitz and Burrows, 2004](#); [Buchwitz et al., 2005a](#)). Other groups use somewhat different but also highly simplified approaches to deal with aerosol variability. For example in FSI/WFM-DOAS ([Barkley et al., 2006a,b,c, 2007](#)) three “climatological” aerosol scenarios (maritime, rural, and urban) are used (instead of one as in WFM-DOAS) depending on the location of the satellite footprint. This approach is not considered to be superior compared to our approach as it also does not take aerosol variability fully into account and might introduce

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additional complications such as discontinuities of the retrieved CO₂ near cities and coast lines.

Future studies will show to what extent aerosol related errors can be reduced by taking aerosol variability better into account in the radiative transfer used to determine XCO₂ but at present we only identify aerosols and filter the data to remove strongly aerosol contaminated scenes.

4 Error analysis

The retrieved carbon dioxide and oxygen vertical columns exhibit a random error due to instrument noise depending on the signal-to-noise ratio and thus on surface albedo and characteristics of the detector of the respective channel. This results in a single measurement precision of about ~1% for the retrieved CO₂ columns and because of the much better signal-to-noise ratio in the O₂ A band spectral region (around 760 nm; SCIAMACHY channel 4) in a considerably smaller random error of the O₂ column of about ~0.3%. Hence, the upper bound of the theoretical precision of the XCO₂ can be estimated to be slightly larger than 1% using radiative transfer simulations and the instrument's signal-to-noise performance. To estimate the single ground pixel retrieval precision of the real in-orbit measurements we determined for several locations daily standard deviations of the retrieved XCO₂ (because of the orbit geometry this basically corresponds to the standard deviation of all the data from a single overpass at around 10:00 a.m. local time). We averaged the daily standard deviations determined from all the SCIAMACHY XCO₂ retrievals at a given location for all days where at least 10 measurements pass the quality filter in a radius of 350 km around that location. This average XCO₂ standard deviation can be interpreted as an upper limit of the single ground pixel retrieval precision (as it is also influenced by the variability of atmospheric CO₂). This analysis was performed for Park Falls (USA), Bremen (Germany), and Darwin (Australia) providing a consistent estimate of the precision error of about 5–6 ppm, respectively, which corresponds approximately to 1.5% and is therewith close

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to the expected theoretical value.

In addition to instrument noise there are several other error sources such as errors resulting from the variability of temperature and water vapour profiles, aerosols, clouds, and surface spectral reflectivity. Most of these errors were already quantified for earlier versions of WFM-DOAS (Buchwitz and Burrows, 2004; Buchwitz et al., 2005a). Because of the improved albedo treatment in version 1.0, with albedo retrieval and the extended look-up table interpolation/extrapolation method, the albedo related XCO₂ errors shown in Table 1, which could be as large as a few percent in the previous version, are now significantly reduced and essentially negligible (absolute value $\lesssim 0.1\%$) for typical albedos assumed to be wavelength independent in a given spectral fitting window. Table 2 shows the retrieval errors for different natural surface types taking the full spectral albedo dependence (also within the small spectral fitting windows) into account. As can be seen, the retrieval errors are well below one percent for typical surfaces with the exception of snow where the very high albedo (close to 1) in the O₂ fitting window leads to a somewhat higher error. However, snow- and ice-covered surfaces are typically filtered out as a side-effect of the PMD cloud detection. Otherwise an observable XCO₂ underestimation would be expected. The albedo related errors for surface types with albedos higher than 0.3 in at least one fitting window can be further reduced by adding additional albedos to the reference spectra in the future.

The XCO₂ retrieval error due to surface elevation (mean surface pressure) variations (e.g., along the orbit) is also considerably reduced due to the better consideration of surface elevation changes dropping for example from 2.5% in version 0.4 for a surface elevation of 400 m (Buchwitz et al., 2005a) to 0.3% in version 1.0 by using the new altitude interpolation/extrapolation scheme.

To estimate the retrieval error due to aerosols several aerosol scenarios have been defined (see Tables 3 and 4), the default scenario used for the look-up table generation being characterized as follows: Maritime aerosol in the boundary layer (BL), tropospheric visibility and humidity 23 km and 80%, respectively, background stratospheric, and normal mesospheric conditions. Besides the rather extreme scenario

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with strongly enhanced aerosol in the boundary layer (urban aerosol in the BL with visibility of only 2 km and relative humidity of 99%), three additional more typical scenarios are considered (using Mie phase function instead of the Henyey-Greenstein parameterization used for the LUT default scenario): (i) “OPAC background” consists of continental relatively clean aerosol in the BL and the free troposphere (99.998% water soluble), (ii) “OPAC continental” has continental polluted aerosol in the boundary layer (31.399% water soluble and 68.6% soot) and continental average aerosol (45.79% water soluble and 54.2% soot) in the free troposphere, and (iii) “OPAC desert” consists of desert aerosol (93.19% mineral – nucleation mode – and 6.81% mineral –accumulation mode–) in the boundary layer and the continental clean aerosol type in the free troposphere. For these three scenarios the sensitivity to aerosols is less than 1%. However, in extreme situations (e.g., very high boundary layer aerosol) the error can be as high as about 5% because the sensitivity in the O₂ A-band is significantly larger than in the NIR in these cases. Therefore strongly aerosol contaminated scenes are filtered out as described in Sect. 3.4.

In order to examine the sensitivity to the variability of temperature, pressure, and trace gas vertical profiles, simulated spectra for several model atmospheres (extracted from MODTRAN; Berk et al., 1998) have been generated while the WFM-DOAS look-up table is based on the US Standard Atmosphere. The analysed atmospheres differ from the US Standard Atmosphere with respect to temperature, pressure and water vapour profiles; the resulting retrieval errors are shown in Table 5. As can be seen, the XCO₂ errors are less than 1% for all cases.

The investigation of errors resulting from profile variability has been extended focussing on an error analysis relevant for the CO₂ seasonal cycle. To specify the errors originating from unconsidered variability of temperature and trace gas profiles (WFM-DOAS uses a single profile in each case for the retrieval), simulated spectra have been generated using ECMWF temperature and water vapour profiles as well as carbon dioxide profiles from NOAA’s CarbonTracker model (described below). Park Falls was chosen as a reference location for this study because it is representative for northern

hemispheric mid-latitudes and because the choice of this site is helpful in estimating the error of the retrieved XCO₂ seasonal cycle when comparing with the Park Falls FTS (see Sect. 5).

As one can see in Fig. 8, the CO₂ and O₂ vertical column errors due to temperature profile variability cancel to a large extent when calculating the CO₂ to O₂ column ratio, i.e., the CO₂ mole fraction, because both absorption bands respond similar to temperature changes. The water vapour profile related error is negligible because the spectral fitting windows have been selected such that interference with water vapour absorption is small. Additionally a weighting function (radiance derivative) for water absorption is included in the CO₂ fit and an iteration regarding water vapour is implemented in the algorithm further minimizing this error. From the three error sources investigated, the dominating error is the carbon dioxide vertical profile variability error which is about 0.8% peak-to-peak. When all three error sources are considered together, the total XCO₂ retrieval error is 1.0% peak-to-peak. These findings are consistent with a similar error analysis for WFM-DOAS performed by Barkley et al. (2006a) restricted to CO₂ total column retrieval. The CO₂ mixing ratio profile variability error has been defined as the deviation of the retrieved XCO₂ from the true XCO₂. When the retrieved XCO₂ is compared with global models or when the retrieved XCO₂ is used for inverse modelling, this error can be reduced by applying the known SCIAMACHY CO₂ column retrieval averaging kernels (which characterizes the altitude sensitivity of the CO₂ measurements) to the model CO₂ vertical profiles. The remaining error is the so called smoothing error which can be estimated when the uncertainty of the model profile is known (typically this is done by using an estimate of the covariance matrix of the model profile).

5 Discussion of the multi-year XCO₂ data set

All SCIAMACHY spectra (Level 1b version 5 converted to Level 1c using the standard calibration) for the years 2003, 2004, and 2005 which have been made available by ESA/DLR, have been processed using the improved retrieval algorithm WFM-DOAS

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version 1.0.

5.1 CO₂ yearly averages and annual increase

Figure 2 shows, as an example, the CO₂ and O₂ total column annual averages for the year 2003. It can be seen that the spatial variations are very similar ($r=0.98$) because both gases are long-lived and therefore well mixed in the atmosphere; hence the columns are primarily reflecting Earth's topography. The small CO₂ source and sink signals we are primarily interested in are hidden in the tiny differences between the CO₂ columns and the O₂ columns. These signals can be made visible by computing XCO₂, i.e., the column-averaged dry air mole fraction of CO₂, which is the ratio of the CO₂ column and the dry air column. The dry air column is obtained by dividing the O₂ column (shown in the bottom panel) by 0.2095, which is the mixing ratio of O₂ in dry air. The corresponding SCIAMACHY XCO₂ for 2003 is shown in Fig. 3. For all three quantities derived from SCIAMACHY, the CO₂ and O₂ columns and XCO₂, the same filtering criteria have been applied.

The resulting annual composite averages for XCO₂, which meet the classification "good" defined above, are shown in Fig. 3 (left hand side panels). A significant part of the CO₂ spatial variations shown in Fig. 3 result from the irregular sampling of the SCIAMACHY XCO₂. For example, the mid and high latitudes of the Northern Hemisphere are strongly weighted towards late spring, summer, and early autumn, where CO₂ is known to be much lower than for the (true) yearly average. This uneven weighting is due to the significantly higher cloud cover in winter but also because of larger solar zenith angles and snow coverage. As a result, most of the measurements in winter are automatically filtered out by the implemented quality filtering scheme. To assess the quality of the measured WFM-DOAS CO₂ mole fractions globally we performed a comparison with the XCO₂ obtained from the global CO₂ assimilation system CarbonTracker (Peters et al., 2007). The corresponding CarbonTracker XCO₂ is shown in the right hand side panels of Fig. 3.

CarbonTracker has been developed by NOAA ESRL in cooperation with many part-

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ners. CarbonTracker (see also <http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/>) is a reanalysis of the recent global surface fluxes of carbon dioxide, as estimated from a large set of atmospheric CO₂ mole fractions produced via a data assimilation system. The underlying atmospheric transport model TM5 (Krol et al., 2005) is driven by meteorological data from ECMWF. The CarbonTracker XCO₂ field as used for this study has been sampled in space and time as the SCIAMACHY satellite instrument measures. The SCIAMACHY altitude sensitivity has been taken into account by applying the SCIAMACHY CO₂ column averaging kernels (Buchwitz et al., 2005a) to the CarbonTracker CO₂ vertical profiles (the difference between applying or not applying the SCIAMACHY averaging kernels is quite small, typically less than 1 ppm). Concerning the accuracy of CarbonTracker, NOAA's comparison to about 14,000 independent aircraft profiles sampled mostly over North America shows agreement within one standard deviation of ±1.9 ppm over multiple years, distributed as ±1.5 ppm in winter, and ±2.7 ppm in summer; biases are within 0.5 ppm in each season and nearly zero for the multiyear average (Wouter Peters, NOAA, personal communication; see also the CarbonTracker product evaluations website <http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/profiles.php> showing agreement within typically ±4 ppm). For all comparisons with CarbonTracker the SCIAMACHY CO₂ data have been scaled by a constant factor of 1.015 to compensate a small systematic bias between the two data sets, which is, however, uncritical for application in inverse modelling as constant biases can be relatively easy corrected, especially if they are known.

As can be seen in Fig. 3, the CO₂ pattern as retrieved from SCIAMACHY are similar for all years but shifted upwards from one year to the next due to a general quite homogeneous increase of the retrieved CO₂ with time (see also discussion in Sect. 5). This can also be seen in the CarbonTracker XCO₂. The observed CO₂ increase is also demonstrated by the linear fits shown in Fig. 10 which are almost identical to CarbonTracker, and amount to about 1.0% from the beginning of 2003 to the end of 2005. In this context it is important to point out, as already explained earlier, that no a-priori information is used about increasing CO₂ in the retrieval procedure. A

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more quantitative discussion of this is given in [Buchwitz et al. \(2007b\)](#). The main difference between the SCIAMACHY XCO₂ and the CarbonTracker XCO₂ is that the retrieved XCO₂ spatial pattern are about a factor of two more variable (about ±12 ppm for SCIAMACHY compared to about ±6 ppm for CarbonTracker).

5.2 CO₂ seasonal cycle

To validate the retrieved XCO₂ data, the SCIAMACHY WFM-DOAS version 1.0 XCO₂ has been compared with Fourier Transform Spectrometer (FTS) measurements performed at Park Falls, Wisconsin, USA ([Washenfelder et al., 2006](#)) (obtained from <http://www.tcon.caltech.edu/>) and at Bremen, Germany (Macatangay et al., 2008¹)

Figure 9 shows the comparison between the FTS and SCIAMACHY data sets for both locations based on monthly averages. For the XCO₂ data from SCIAMACHY a radius of 350 km around the measurement site has been selected and the monthly composite is made of XCO₂ data classified as 'good', which fall within this region. The data are plotted as anomalies, i.e., with SCIAMACHY and FTS mean values subtracted (on average the SCIAMACHY data are about 1–2% lower than FTS; the exact biases are given in Fig. 9, see d%). To maximize the number of SCIAMACHY data points we used a slightly relaxed WFM-DOAS quality criterion (allowing an O₂ fit residuum RMS up to 0.025 instead of the standard value of 0.02). As can be seen, despite the larger scatter of the single measurement of SCIAMACHY XCO₂, which is on average about 9 ppm, good agreement is obtained for the monthly composite averages with respect to the amplitude and the phase of the seasonal cycle of CO₂ over Park Falls. The correlation coefficient between the two data sets is 0.94. For the standard quality filtering with somewhat less data points available for comparison, the correlation coefficient is 0.88. The agreement with the FTS in Bremen is somewhat worse ($r=0.73$) most likely be-

¹Macatangay, R., Warneke, T., Gerbig, C., Körner, S., Heimann, M., and Notholt, J.: Spatial Variability of Column Averaged VMRs of CO₂ over Bremen, Germany, manuscript in preparation, 2008.

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cause of the larger variability of the atmospheric CO₂ in northern Germany, with many local sources compared to Park Falls. Assuming that the time dependence of the total peak-to-peak XCO₂ measurement error from the error analysis in Sect. 4 is perfectly correlated with the CO₂ seasonal cycle, which is not exactly the case, the upper bound of the error of the amplitude of the measured CO₂ seasonal cycle due to the examined error sources is estimated to be 0.5% or 2 ppm (half of the total XCO₂ peak-to-peak measurement error determined in Sect. 4).

Similar results have been reported recently for a comparison of SCIAMACHY CO₂ retrieved using FSI/WFM-DOAS (Barkley et al., 2007) with the Park Falls FTS data. Based on a comparison of daily data, Barkley et al. (2007) report correlation coefficients in the range 0.36–0.73 (their Table 1) depending on spatial collocation with typically higher correlation for the more relaxed spatial collocation limits. For monthly mean data Barkley et al. (2007) also report a correlation coefficient of 0.94 as found here for WFM-DOAS. Similar remarks apply to the 1–2% low bias of the SCIAMACHY XCO₂ relative to the Park Falls FTS. Furthermore, also the scatter of the single ground pixel XCO₂ retrievals of the two independently generated SCIAMACHY data sets is similar (on average about 9 ppm).

A hemispheric comparison of the WFM-DOAS version 1.0 XCO₂ with CarbonTracker based on daily data is shown in Fig. 10. As can be seen, the retrieved XCO₂ seasonal cycle over the Northern Hemisphere shows good agreement with CarbonTracker ($r=0.86$). The northern hemispheric amplitude of the seasonal cycle retrieved by SCIAMACHY (6 ppm) is however somewhat larger than for CarbonTracker (4 ppm).

The seasonal variation, as measured by SCIAMACHY, is however significantly different for the Southern Hemisphere concerning both amplitude (4–5 ppm for SCIAMACHY compared to 1–2 ppm for CarbonTracker) as well as phase. Olsen et al. (2004) report a seasonal amplitude of ~3 ppm for southern hemispheric Africa and South America derived from independent model simulations. Figure 10 shows that the SCIAMACHY XCO₂ over the Southern Hemisphere is significantly noisier (larger scatter of the daily means) compared to the Northern Hemisphere. This is because of the smaller (ice

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and snow free) landmass in the Southern Hemisphere, to which the SCIAMACHY data are restricted, resulting in less data available for averaging. This may contribute to the larger differences to CarbonTracker over the Southern Hemisphere compared to the Northern Hemisphere but probably cannot explain the significantly different seasonal cycles. Figure 11 shows the column amounts of SCIAMACHY carbon dioxide and oxygen in comparison to CarbonTracker (computed from surface pressure and CO₂ mole fraction). The deviations from CarbonTracker of the column amounts have a very similar structure in the Northern Hemisphere and cancel to a large extent when computing the mole fraction XCO₂ leading to the good agreement demonstrated in Fig. 10. In the Southern Hemisphere the small additional negative offset in both columns cancels perfectly when computing the ratio.

A possible explanation for the deviation of the resulting SCIAMACHY XCO₂ seasonal variations from CarbonTracker in the Southern Hemisphere could be a SZA (or airmass) dependent error resulting for example from neglecting polarization in the radiative transfer (Natraj et al., 2006) or from errors in the spectroscopic data, e.g., errors of the air-broadened half width of the CO₂ and/or O₂ absorption lines, as discussed in Washenfelder et al. (2006) for the Park Falls XCO₂ FTS measurements. Such kind of errors can contribute to the differences shown in Fig. 10 but probably cannot fully explain the difference to CarbonTracker over the Southern Hemisphere because of the much better agreement with CarbonTracker over the Northern Hemisphere. If a SZA dependent error for example due to errors in the spectroscopic data would be the only reason for the difference of the SCIAMACHY and CarbonTracker seasonal cycles, then the difference should be similar for both hemispheres except for a six months phase shift. This however is not the case.

Nevertheless, spectroscopic errors may contribute to the differences shown in Fig. 10 and we estimated the sensitivity of the retrieved XCO₂ to changes in the CO₂ and O₂ absorption line width. Why can line width errors result in a SZA dependent CO₂ or O₂ column retrieval error? This can be explained by increasing “saturation” of the depth of non-resolved strong absorption lines with increasing absorber amount along the light

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path (Goody and Yung, 1989), an effect which is also nicely illustrated in Frankenberg et al. (2005) for SCIAMACHY methane measurements (see their Figs. 1 and 2). Here saturation refers to the decrease of the sensitivity of the (logarithm of the) measured spectrum to changes in the absorber amount along the light path, for example due to an increasing SZA. As a wider line shows less saturation (in the line center) compared to a narrower line (assuming identical line intensities and line shape functions), and because the SZA dependence of the saturation will be different for the two lines, a line width error may result in a SZA dependent retrieval error. Therefore one typically would expect an underestimation (overestimation) of the retrieved column which increases with increasing SZA, if the line width is in reality narrower (wider) than assumed for the retrieval (a narrower monochromatic line is deeper compared to an equivalent wider line, but if the lines are strong and not resolved, the opposite is true). To quantify this error we performed retrievals based on simulated spectra for a range of solar zenith angles for different assumed air-broadened line width errors (assuming that the width of all lines change identically by a certain percentage). The values we report here are for the two extreme solar zenith angles, namely 15° (which is approximately the lowest SZA encountered by SCIAMACHY) and 75° (the upper limit accepted for this study). We found that if all CO_2 lines would (in reality) be narrower by 1% compared to the air-broadened line widths currently assumed for retrieval (HITRAN 2004, Rothman et al., 2005), this would result in retrieved CO_2 column being underestimated by $\sim 0.4\%$ for a SZA of 15° and by $\sim 0.5\%$ for a SZA of 75° , i.e., the underestimation increases with increasing SZA, in agreement with the discussion given above, by 0.1% for CO_2 . For O_2 we found a larger offset, but a negligible SZA dependence compared to CO_2 . This means that the SZA dependent part of the XCO_2 error appears to be dominated by the SZA dependent part of the CO_2 column error, i.e., 0.1% if the line widths would be off by 1%. We repeated this investigation for a range of line width errors and SZAs and found that the SZA dependent part of the XCO_2 error depends to a good approximation linearly on the assumed line width error resulting in an approximately 0.5 ppm XCO_2 error (peak-to-peak) per 1% line width error (the results for Lauder, New Zealand, are

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shown in Fig. 12). This means that the differences to CarbonTracker over the Southern Hemisphere of about 6 ppm peak-to-peak would correspond to an air-broadened line width error of 12% which is higher, but not very much higher, than the uncertainty of the spectroscopic data which are 5–10% for CO₂ (2–5% for O₂). Finally we would like to point out that the retrieved XCO₂ over the Southern Hemisphere (or, more precisely, the difference to CarbonTracker) is (anti-)correlated with the SZA, which has a maximum in winter, i.e., in the middle of the year. This is not true, however, for the Northern Hemisphere, as the difference to CarbonTracker is not symmetric with respect to the middle of the year. From this one can conclude that a SZA dependent error, for example due to spectroscopic errors, may contribute significantly to the differences between the SCIAMACHY and CarbonTracker XCO₂ shown in Fig. 10 but cannot explain all the differences.

Figure 13 shows global bi-monthly maps of the XCO₂ spatial pattern observed when sampling the seasonal cycle during its (northern hemispheric) XCO₂ maximum and minimum time periods. Significant seasonal variability is visible in both the SCIAMACHY and the CarbonTracker data. This variability of the CO₂ spatial pattern is dominated by the seasonal uptake and release of CO₂ by the Northern Hemisphere terrestrial biosphere, resulting in much lower XCO₂ during July/August compared to, e.g., May/June in the northern hemispheric mid and high latitudes covered by, e.g., the boreal forests. Figure 13 shows that both data sets, SCIAMACHY and CarbonTracker XCO₂, are clearly correlated. The SCIAMACHY data show however significantly larger variability; for this reason two different color scales have been used for Fig. 13 (± 14 ppm for SCIAMACHY compared to ± 9 ppm for CarbonTracker).

5.3 CO₂ regional pattern

To enable a more detailed comparison on the regional scale, Figs. 14 and 15 show monthly composite averages of the satellite data and CarbonTracker over large parts of the Northern Hemisphere, namely USA, Canada and Eurasia. The horizontal resolution of the maps shown in Figs. 14–15 is 7° × 7°. The data are shown as anomalies,

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i.e., the mean value has been subtracted for each map to be able to better compare the spatial pattern. As can be seen, the two independent XCO₂ data sets are clearly correlated in space and time indicating that the satellite data capture spatio-temporal atmospheric CO₂ variability on a regional scale. Many of the larger scale features which show up in the CarbonTracker XCO₂ are also visible in the satellite data, for example the extended region of low XCO₂ over eastern Canada in August 2005 and the relatively high XCO₂ over the southern USA in particular in July and August. There are however also significant differences. The differences with respect to CarbonTracker shown in Figs. 14 and 15 cannot be explained by a possible SZA dependent retrieval error discussed in the previous section, as the variation of the SZA is small for the maps shown in Figs. 14 and 15 (especially in the east to west direction where the SZA is essentially constant) and because only XCO₂ anomalies are shown, i.e., the XCO₂ mean value (which could be affected by a SZA dependent error) has been subtracted for each map. Typically the retrieved variability in the SCIAMACHY data product is about 4 ppm (~1% of 380 ppm) higher compared to CarbonTracker. But depending on time and location the differences can exceed 8 ppm. Similar conclusions can be drawn for other time periods (2003 and 2004) and other regions (e.g., South America), not shown here. A clear interpretation of the differences to CarbonTracker cannot be offered at present. As discussed in Sect. 5 the estimated accuracy of CarbonTracker is about a few ppm. In the error analysis of the WFM-DOAS retrieval algorithm presented in Sect. 4 we have identified several error sources which may contribute to the overall error of a single measurement. Most of the individual errors are typically less than 1% for a single measurement but the results shown in Figs. 14–15 are averages over many individual measurements. The random error (precision) is probably very small, much smaller than 1%, but it is difficult to reliably estimate the systematic error which remains after averaging many individual measurements; the overall systematic error can be smaller but also larger than 1%. One can however assume that the errors of the CarbonTracker and the satellite XCO₂ are uncorrelated. In this case the 1-3 percent systematic differences between the satellite and the CarbonTracker XCO₂

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anomalies may be interpreted as an upper limit of the relative accuracy of the satellite XCO₂. Based on this one may conclude that the relative accuracy of the satellite XCO₂ is about 1–2%.

In order to determine if regionally elevated CO₂ originating from anthropogenic CO₂ emissions can be detected, we averaged all the SCIAMACHY XCO₂ retrievals for the years 2003–2005. Figure 16 shows the resulting map (resolution 0.5°×0.5°) for Germany and surrounding countries. As can be seen, the SCIAMACHY XCO₂ correlates reasonably well with population density (CIESIN/CIAT, 2005) and EDGAR anthropogenic CO₂ emissions (EDGAR 3.2 Fast Track 2000 dataset (32FT2000) Olivier et al., 2005). All three data sets show an extended region of high values covering the region southern Netherlands/north-western Belgium/western Germany. Shown is also the CarbonTracker XCO₂. The comparison with CarbonTracker however does not allow a quantitative comparison at a resolution of 0.5°×0.5° as the resolution of the CarbonTracker XCO₂ data set used for this study is not high enough (4°latitude×6°longitude). Despite the mismatch of the resolution one can see some correlations with the SCIAMACHY XCO₂, e.g., elevated XCO₂ especially over northern Belgium/southern Netherlands and over northern Germany. The elevated CO₂ over northern Germany, visible in both the SCIAMACHY and the CarbonTracker XCO₂, is not well correlated with population density and the EDGAR CO₂ emissions and may result from transport in combination with the rather poor sampling of the SCIAMACHY XCO₂ measurements (the number of measurements per grid cell is about 35 for Germany; the averaging is strongly weighted towards cloud free days in late spring, summer, and early autumn; see global monthly composite maps for 2003–2005 on the WFM-DOAS website http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/index.html). This transport aspect needs further study using higher resolution CarbonTracker XCO₂ data sets in the future. Figure 16 shows that the XCO₂ regional enhancements are only on the order of 1 percent (4 ppm) even for regions of very strong emissions sources (emitting several 10 Tg (=Mt) CO₂ per year). This is due to the large amount of CO₂ already contained in the atmosphere in combination with the quite large ground pixel size of

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SCIAMACHY (note that 370 ppm XCO₂ corresponds to about 10Mt CO₂ in a single ground pixel of size 30×60 km²). Nevertheless, Fig. 16 indicates that elevated CO₂ originating from regional anthropogenic CO₂ emissions can be detected. To the best of our knowledge regionally elevated CO₂ arising from anthropogenic CO₂ emissions has until now not been detected using measurements from space.

6 Conclusions

We have presented and discussed a multi-year global data set of atmospheric carbon dioxide column-averaged dry air mole fractions, XCO₂. The XCO₂ data set has been retrieved from the spectral near-infrared nadir observations of the SCIAMACHY instrument onboard the European environmental satellite ENVISAT using the significantly improved version 1.0 of the retrieval algorithm WFM-DOAS. The quality of the global SCIAMACHY XCO₂ data set has been assessed by a combination of an error analysis using simulated retrievals, comparisons with a limited number of independent XCO₂ measurements obtained using ground-based FTS, and comparisons with XCO₂ from NOAA's global assimilation system CarbonTracker.

The largest differences with respect to the reference data which we have identified were over the Sahara where SCIAMACHY XCO₂ is overestimated by a few percent under conditions of highly elevated desert dust storm aerosol as identified using TOMS/Earth Probe Absorbing Aerosol Index (AAI) (Herman et al., 1997). We have shown that XCO₂ has smaller errors in this case than the absolute CO₂ columns due to cancellation of errors when dividing the retrieved CO₂ columns by simultaneously retrieved O₂. We found however that this does not fully eliminate all aerosol related errors. Therefore, for most of the results presented here, we have applied a threshold filter based on the AAI to remove strongly aerosol contaminated scenes.

Currently, the CO₂ column-averaged dry air mole fraction is only measured at a few ground stations and only recently by a new network of FTS stations (see, for example, the Total Carbon Column Observing Network (TCCON) website: <http://>

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//www.tcon.caltech.edu). The comparison of the SCIAMACHY XCO₂ with the XCO₂ FTS measurements at Park Falls, Wisconsin, USA and Bremen, Germany, which are both part of TCCON, showed good agreement with respect to the amplitude and the phase of the CO₂ seasonal cycle for the monthly composite averages.

To assess the quality of the data globally, we have performed comparisons with the recently released output of NOAA's global assimilation system CarbonTracker. To enable a meaningful comparison, the CarbonTracker data have been sampled in space and time as SCIAMACHY measures and the SCIAMACHY averaging kernels have been applied to CarbonTracker to take the altitude sensitivity of the SCIAMACHY CO₂ retrievals into account. In general we found reasonable to good agreement with CarbonTracker, for example concerning the increase of carbon dioxide with time globally and concerning the CO₂ seasonal cycle over the Northern Hemisphere where a large uptake of atmospheric CO₂ is observed typically in July and August. This uptake is attributed primarily to vegetation during the growing season, i.e., by the terrestrial biosphere. On the regional scale the satellite data show in general similar spatial pattern as CarbonTracker but exhibit typically higher variability.

From the comparison with the limited reference data we conclude that the SCIAMACHY XCO₂ data set over land can be characterized by a systematic low bias of about 1.5% as concluded from the mean difference relative to the FTS and CarbonTracker, and by a relative accuracy of about 1–2% for monthly averages at a horizontal resolution of 7° × 7° as concluded from the comparison of regional XCO₂ anomalies with CarbonTracker. We further estimate the single ground pixel retrieval precision to be about 1–2% (~6 ppm) as concluded, for example, from the mean of the standard deviations of the daily SCIAMACHY XCO₂ at given locations.

When averaging the SCIAMACHY XCO₂ over all three years we find reasonable correlation with EDGAR anthropogenic CO₂ emissions for Germany, The Netherlands and Belgium indicating that regionally elevated CO₂ arising from regional anthropogenic CO₂ emissions can be detected from space.

In summary, we have shown that significant progress has been made in our under-

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standing and the quality of the carbon dioxide data product derived from the SCIAMACHY nadir observations and that the new WFM-DOAS data set comes closer to the demanding accuracy and precision requirements of 1% or better needed for significant CO₂ surface flux uncertainty reduction. We identified primarily two aspects which need further study: (i) the identification of the cause (or causes) of the difference between the SCIAMACHY and CarbonTracker XCO₂ seasonal cycle over the Southern Hemisphere, and (ii) an assessment of the significance of the observed regional XCO₂ spatio-temporal pattern with respect to their information content on regional CO₂ sources and sinks.

The SCIAMACHY XCO₂ data set presented and discussed here is available from the authors on request. Details concerning data format and access as well as supplementary information such as monthly composite maps covering the entire three years time period are given on the SCIAMACHY/WFM-DOAS website http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/index.html.

In the future we will aim at further improving the retrieval algorithm taking into account, for example, updates of the spectroscopic line parameters and better consideration of meteorological parameters (e.g., by taking advantage of temperature and pressure vertical profiles from meteorological analysis) and light path variations (caused by the variability of aerosols, clouds and the surface spectral reflectivity). One of the challenges will be to significantly further improve the accuracy without increasing the computational speed by many orders of magnitude.

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aschi (EC-JRC, Ispra, Italy), P. Wennberg (Caltech), G. Toon (JPL), R. Washenfelder (NOAA), M. Heimann (MPI Biogeochemistry, Jena, Germany), and A. Goede (formerly KNMI, now FOM Institute for Plasma Physics, Nieuwegein, The Netherlands). Funding for this study came from DLR-Bonn (grant 50EE0027 (SADOS), 50EE0727 (SADOS-2) and 50EE0507 (SCIACO2)),
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Table 1. Results of the error analysis for different constant albedos performed by applying WFM-DOAS to simulated SCIAMACHY spectra. The results are valid for a solar zenith angle of 50° and a surface elevation corresponding to sea level.

Albedo	CO ₂ column error [%]	O ₂ column error [%]	XCO ₂ error [%]
0.003	0.63	0.89	-0.26
0.03	-0.01	0.01	-0.02
0.05	-0.05	-0.02	-0.03
0.08	-0.04	-0.01	-0.03
0.10	-0.01	0.01	-0.02
0.15	-0.13	-0.16	0.03
0.20	-0.13	-0.18	0.05
0.30	-0.01	0.01	-0.02
0.40	0.18	0.31	-0.13

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Table 2. As Table 1 but for the spectral albedos of natural materials shown in Fig. 7 taken from the ASTER and USGS spectral libraries.

Surface type	CO ₂ column error [%]	O ₂ column error [%]	XCO ₂ error [%]
Sand (Entisol)	0.13	0.03	0.10
Soil (Mollisol)	0.41	0.13	0.28
Deciduous (Aspen)	0.22	0.17	0.05
Conifers-Meadow	−0.01	0.11	−0.12
Rangeland	−0.11	−0.04	−0.07
Open Ocean	0.06	0.16	−0.10
Medium Snow	0.37	1.83	−1.43

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Table 3. Aerosol scattering (ASOD) and aerosol absorption vertical optical depth (AAOD) in the O₂ and CO₂ fitting windows for the aerosol scenarios used in the error analysis. For comparison the Rayleigh scattering vertical optical depth (RSOD) has also been included.

Aerosol scenario		756 nm	1560 nm
Look-up table default	ASOD:	0.24669	0.17369
	AAOD:	0.00291	0.00307
OPAC background	ASOD:	0.17929	0.04264
	AAOD:	0.00599	0.00557
OPAC continental	ASOD:	0.16420	0.04794
	AAOD:	0.02373	0.01411
OPAC desert	ASOD:	0.22740	0.17568
	AAOD:	0.01406	0.00419
Extreme in BL	ASOD:	2.12661	0.91676
	AAOD:	0.13324	0.07892
	RSOD:	0.02674	0.00145

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Table 4. Results of the error analysis for various aerosol scenarios. The results are valid for an albedo of 0.1, a solar zenith angle of 50°, and a surface elevation corresponding to sea level.

Aerosol scenario	CO ₂ column error [%]	O ₂ column error [%]	XCO ₂ error [%]
OPAC background	−0.61	−0.07	−0.54
OPAC continental	−0.70	−0.05	−0.65
OPAC desert	−0.14	−0.49	0.35
Extreme in BL	−1.16	−6.50	5.71

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Table 5. Retrieval errors resulting from applying WFM-DOAS to various model atmospheres valid for an albedo of 0.1, a solar zenith angle of 50°, and a surface elevation corresponding to sea level. The analysed atmospheres differ from the US Standard Atmosphere used as reference with respect to temperature, pressure and water vapour profiles.

Atmosphere	CO ₂ column error [%]	O ₂ column error [%]	XCO ₂ error [%]
Sub-artic summer	0.04	−0.38	0.42
Sub-artic winter	0.17	0.67	−0.50
Mid-latitude summer	−0.15	−0.55	0.40
Mid-latitude winter	0.47	0.66	−0.19
Tropical	−0.54	−0.68	0.14

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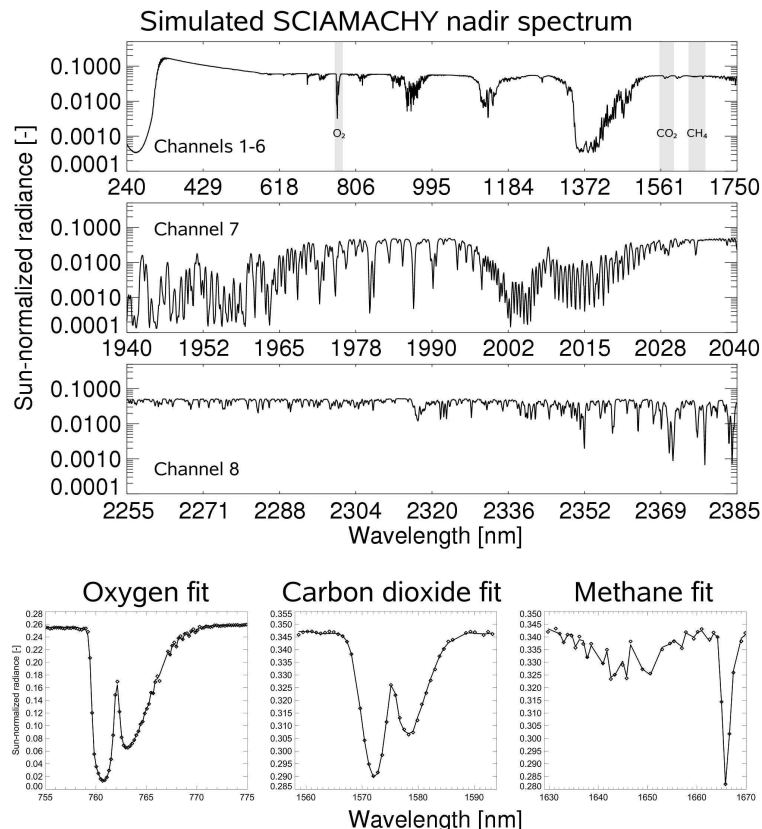


Fig. 1. SCIAMACHY nadir spectrum, simulated with the radiative transfer model SCIATRAN (Buchwitz et al., 2000a,b), covering the entire spectral region observed by SCIAMACHY (top). The three spectral fitting windows for O₂, CO₂, and CH₄ as used by WFM-DOAS version 1.0 are indicated by the shaded areas. WFM-DOAS example fits are shown below (the symbols are the SCIAMACHY measurements, the solid lines correspond to the fitted WFM-DOAS linearized radiative transfer model). A detailed discussion of the methane results is given in Schneising et al. (2008) (Part 2). Shown in the top panel are also channel 7 and channel 8 which cover many CO₂ and CH₄ absorption lines but are not used for WFM-DOAS version 1.0 due to systematic retrieval errors caused by the varying ice layers on the cold detectors.

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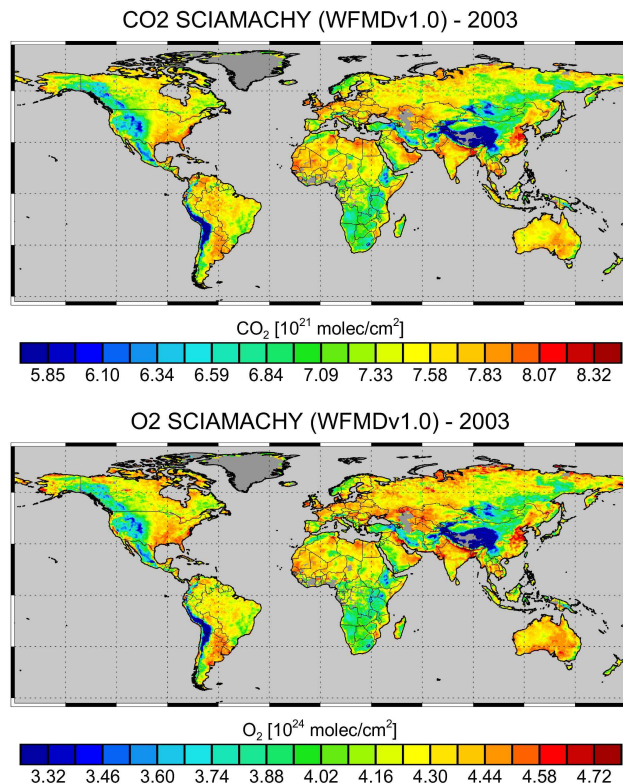


Fig. 2. CO₂ (top) and O₂ (bottom) total vertical columns for the year 2003 as retrieved from SCIAMACHY. Both gases are long-lived and therefore well mixed in the atmosphere; hence the columns of the two gases are well correlated ($r=0.98$) and the spatial pattern primarily reflect the Earth's topography.

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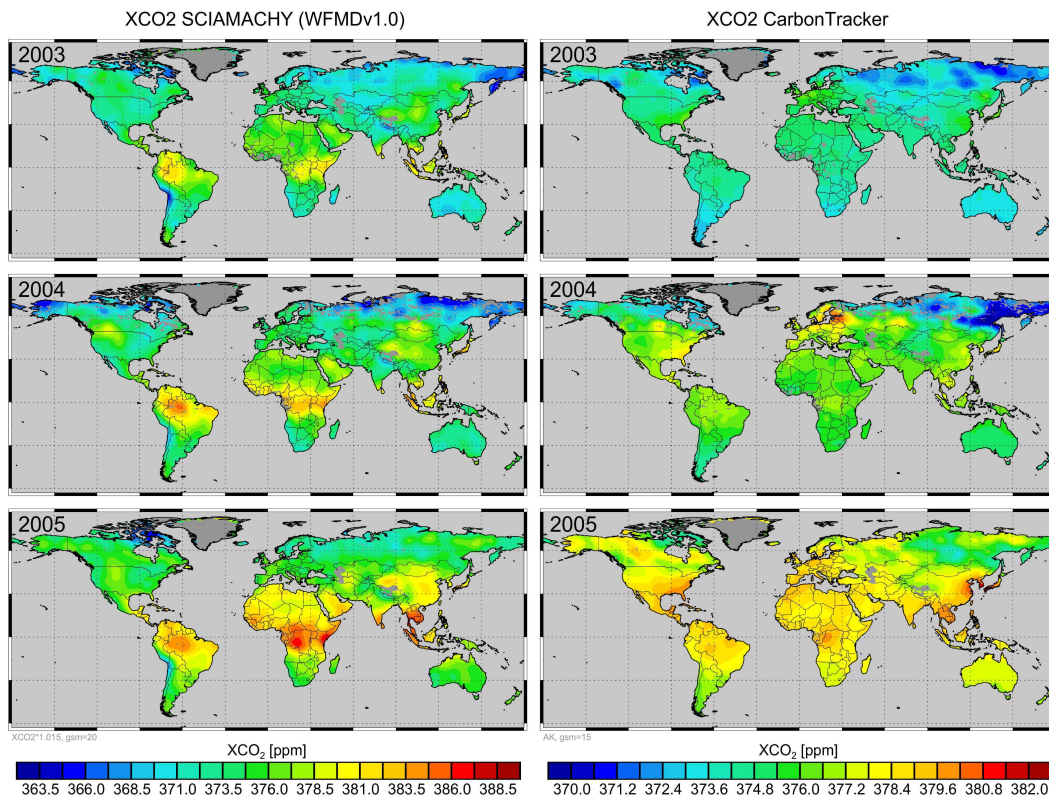


Fig. 3. Three years of SCIAMACHY carbon dioxide column-averaged dry air mole fractions (left) as retrieved by WFM-DOAS version 1.0 (WFMDv1.0) compared to NOAA's CarbonTracker (right) sampled as SCIAMACHY measures. The color scales are different for SCIAMACHY and CarbonTracker to consider the higher variability of the SCIAMACHY XCO₂ (± 12.5 ppm) compared to CarbonTracker (± 6.0 ppm). The SCIAMACHY CO₂ shown here has been aerosol filtered using TOMS/Earth Probe Absorbing Aerosol Index (AAI) (see main text for details).

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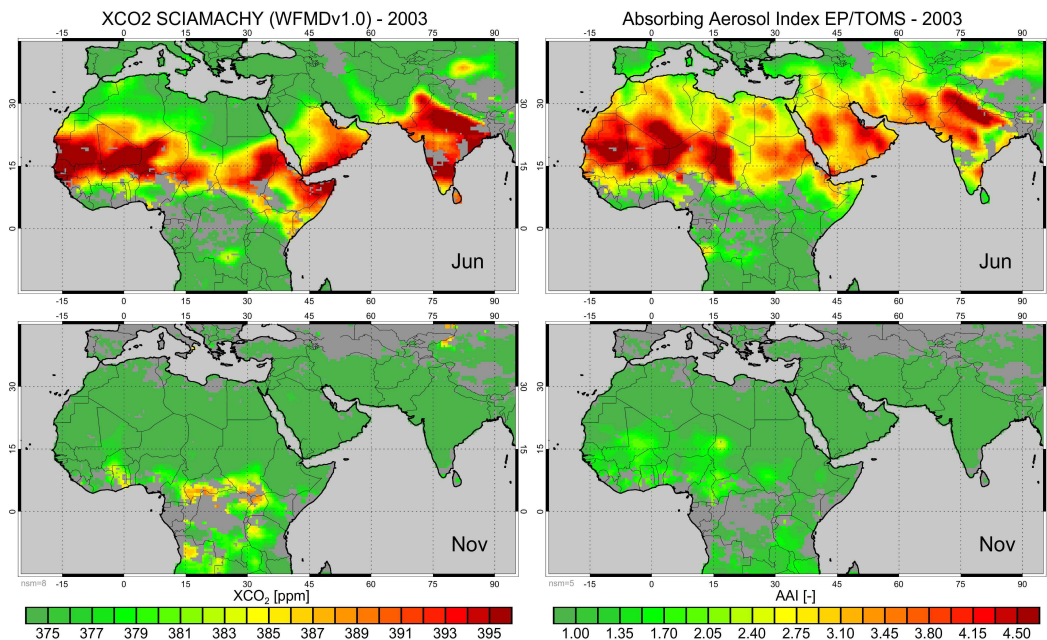


Fig. 4. The left panels shows SCIAMACHY XCO₂ not filtered for aerosol contamination (top: June 2003, bottom: November 2003). The two panels on the right show the Absorbing Aerosol Index (AAI) data product from TOMS/Earth Probe.

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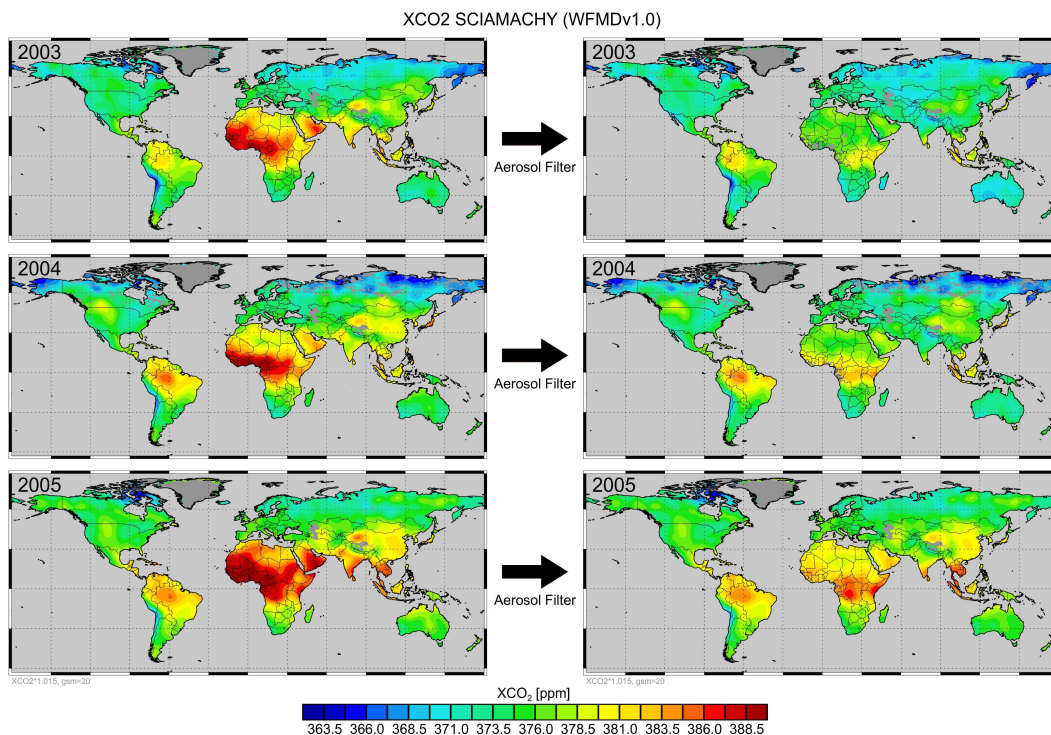


Fig. 5. Yearly averages of SCIAMACHY CO₂ showing the data without (left) and with (right) aerosol (AAI) filtering. The AAI filtered SCIAMACHY data show better agreement with CarbonTracker (see Fig. 3) than the unfiltered data. Note that the panels shown on the right are identical with the left hand side panels of Fig. 3.

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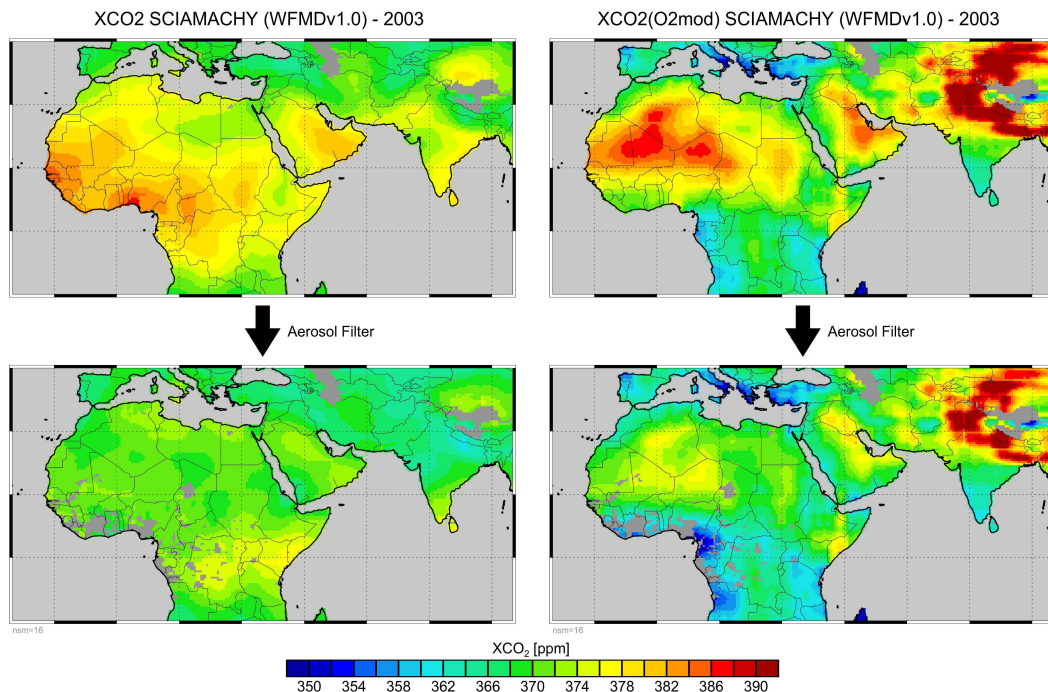


Fig. 6. Comparison between two SCIAMACHY XCO₂ data products. On the left hand side the standard XCO₂ data product is shown which is based on normalizing the measured CO₂ column by the simultaneously measured O₂ column without (top) and with (bottom) AAI (aerosol) filtering applied. On the right hand side the measured CO₂ is normalized using model O₂ columns obtained from CarbonTracker (meteorological) surface pressure.

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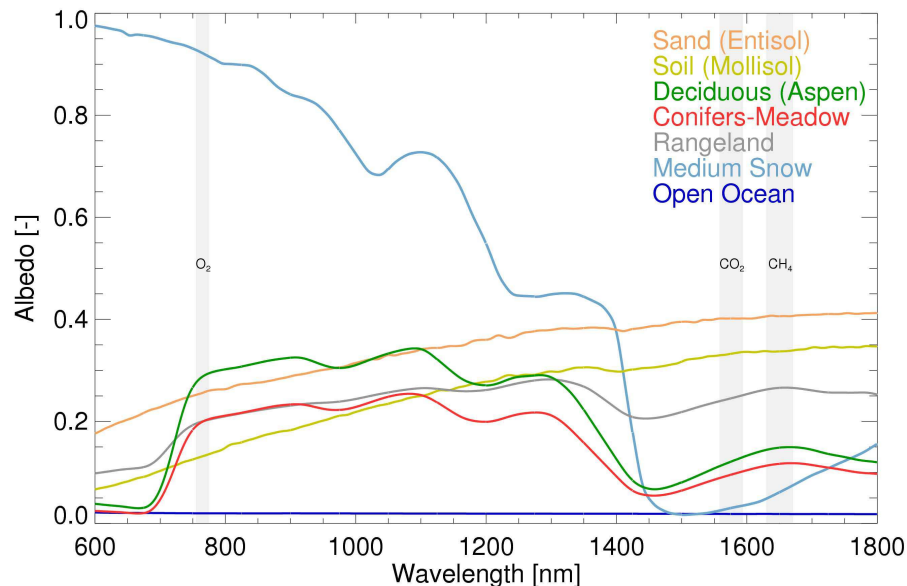


Fig. 7. Spectral albedos of different natural surface types. Reproduced from the ASTER Spectral Library through the courtesy of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California (©1999, California Institute of Technology) and the Digital Spectral Library 06 of the U.S. Geological Survey.

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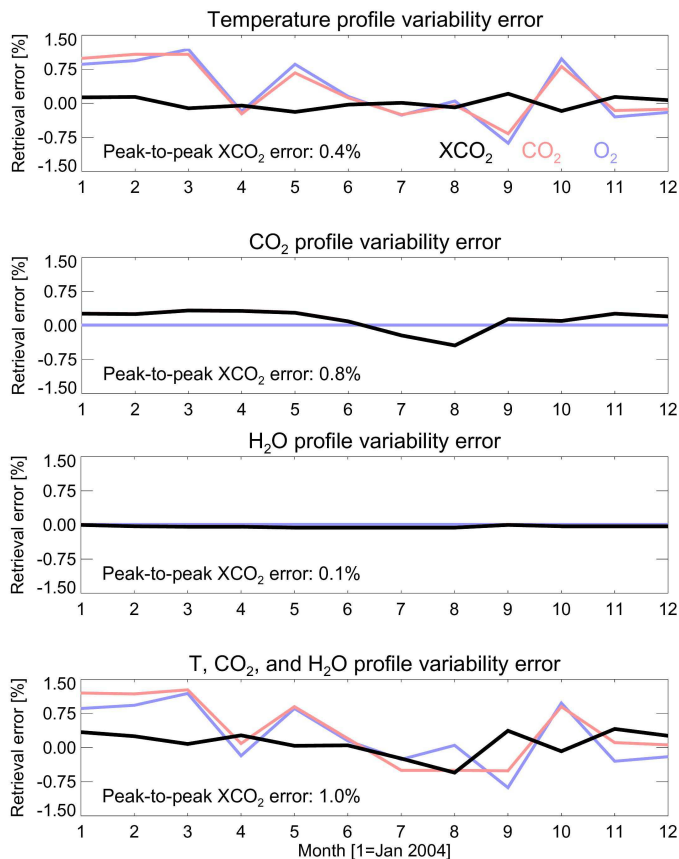


Fig. 8. Results of an error analysis of the SCIAMACHY XCO₂ retrievals based on simulated retrievals focusing on the error of the CO₂ seasonal cycle. For each month simulated spectra have been computed using different vertical profiles of temperature, water vapour, and CO₂. The time dependent temperature and water vapour profiles are from ECMWF; the CO₂ profiles are from CarbonTracker. The simulations correspond to Park Falls, Wisconsin, USA, and are assumed to be approximately representative for northern hemispheric mid-latitudes. The top panel shows the retrieval errors for the CO₂ and O₂ column (in red and blue, respectively) and for XCO₂ (black) due to temperature profile variability. The second panel shows the error due to CO₂ profile variability (for the retrieval a constant CO₂ mixing ratio vertical profile is assumed). The third panel shows the error due to water vapour variability. The bottom panel shows the total error when all three error sources are combined.

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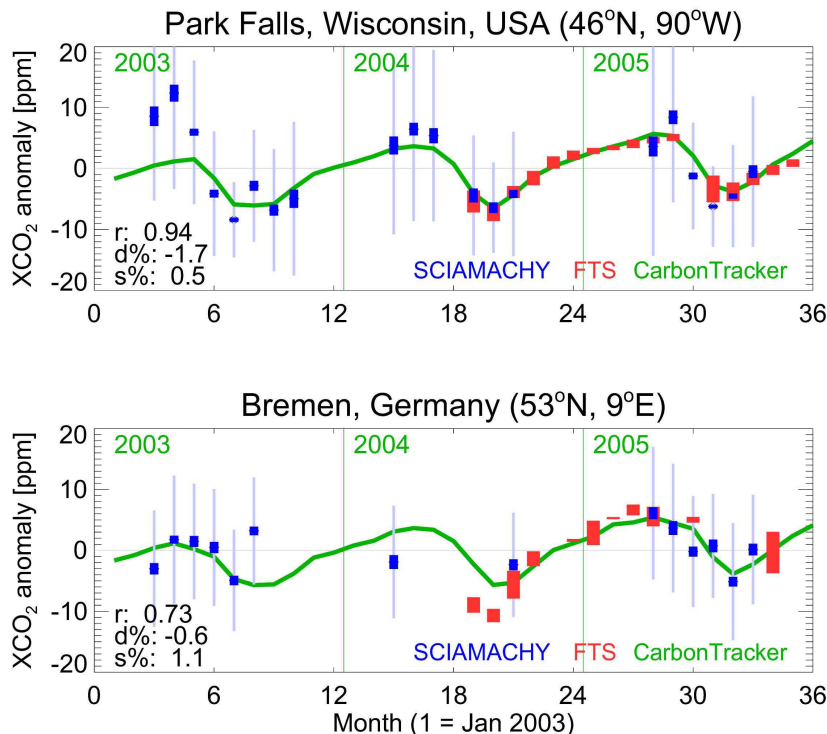


Fig. 9. Comparison of the satellite XCO₂ (blue) with ground based Fourier Transform Spectroscopy (FTS) measurements (red) for Park Falls, Wisconsin, USA (top), and Bremen, northern Germany (bottom). Also included are corresponding CarbonTracker results (green). Shown are comparisons of XCO₂ anomalies, i.e., the corresponding mean values have been subtracted. All quality-filtered SCIAMACHY measurements within a radius of 350 km around the ground station are considered for the comparison. The thin light blue vertical bars correspond to the standard deviation of the SCIAMACHY data within a given month, i.e., correspond to the measured single ground pixel XCO₂ variability. The thicker (darker) blue vertical bars are an estimate of the statistical error of the SCIAMACHY monthly mean XCO₂. The red bars show the standard deviation of the FTS data. The following numbers have been computed based on the monthly averages: *d*% is the mean difference SCIAMACHY–FTS in percent, *s*% denotes the standard deviation of the difference in percent, and *r* is the correlation coefficient. Note that these numbers are valid for the absolute XCO₂, i.e., not for the anomalies, and for SCIAMACHY XCO₂ which has not been scaled by 1.015 (therefore *d*% quantifies the systematic bias of the SCIAMACHY XCO₂ relative to the FTS).

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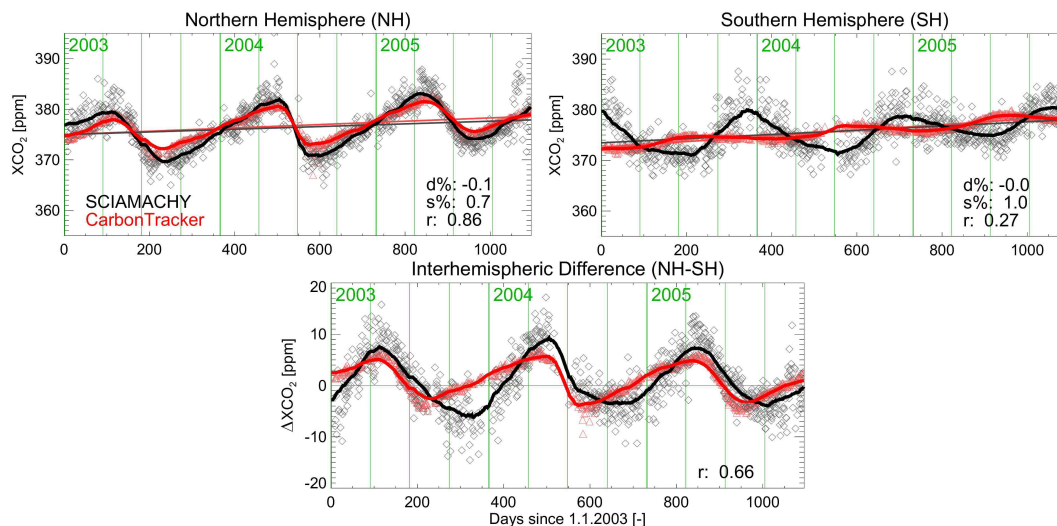


Fig. 10. Comparison of the SCIAMACHY (black) and CarbonTracker (red) XCO₂ for the Northern Hemisphere (top left), the Southern Hemisphere (top right) and for the interhemispheric XCO₂ difference (bottom). For the comparison both the daily SCIAMACHY and CarbonTracker data have been gridded on a common 0.5° × 0.5° latitude/longitude grid. The symbols show the daily average of all coincident grid cells in the corresponding hemisphere. For SCIAMACHY all measurements passing the aerosol filter have been averaged for which the WFMDv 1.0 quality flag indicates a “good” measurement. The solid lines represent a 90 days running average and the straight lines the corresponding linear fits further demonstrating the increase of XCO₂ with time. For each hemisphere the following numbers have been computed based on the (not smoothed) daily averages: $d\%$ is the mean difference SCIAMACHY–CarbonTracker in percent, $s\%$ denotes the standard deviation of the difference in percent, and r is the correlation coefficient. Note that the SCIAMACHY XCO₂ has been scaled with 1.015 to compensate for an approximately 1.5% low bias relative to CarbonTracker (as demonstrated by $d\%$ which is essentially zero).

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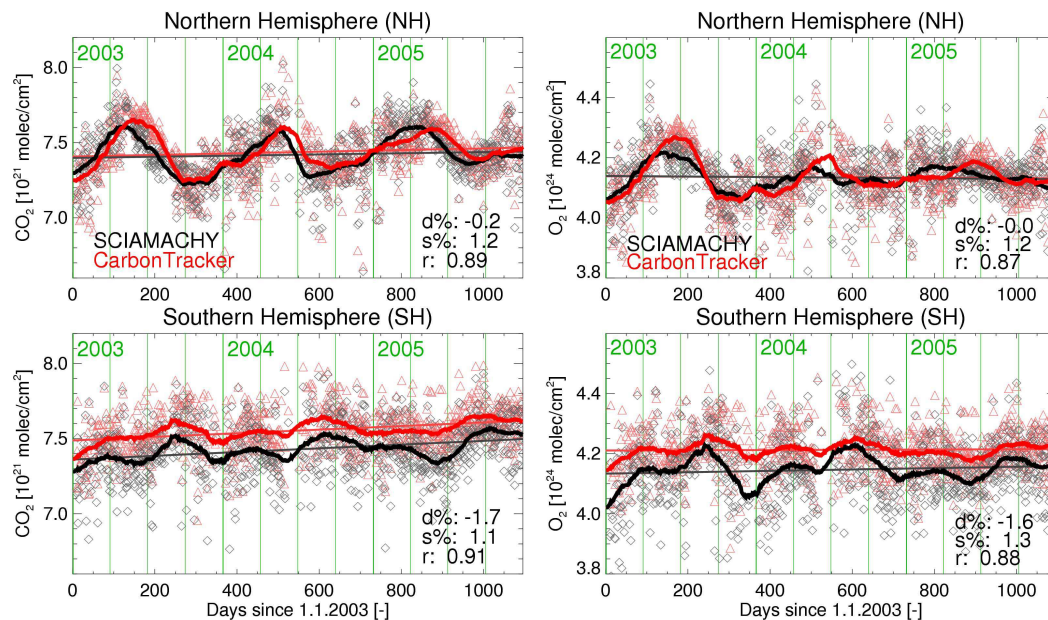


Fig. 11. As Fig. 10 but for the column amounts of carbon dioxide (left) and oxygen (right). The SCIAMACHY CO₂ has been scaled with 1.015. The deviations of the CO₂ and O₂ columns from CarbonTracker have a very similar structure in the Northern Hemisphere (top) and cancel to a large extent when computing the mole fraction XCO₂ leading to the good agreement between SCIAMACHY and CarbonTracker demonstrated in the previous figure. In the Southern Hemisphere (bottom) the small additional negative offset in both columns cancels nearly perfectly when computing the ratio.

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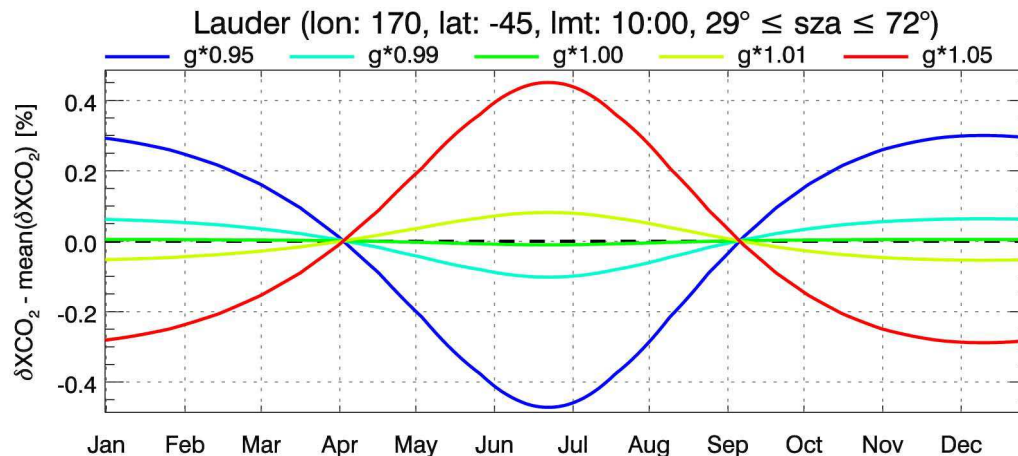


Fig. 12. Sensitivity of the retrieved SCIAMACHY XCO₂ with respect to the CO₂ air-broadened line width for Lauder, New Zealand. Each curve corresponds to a different assumed error of the air-broadened line width. The blue curve, for example, corresponds to a line width error of 5% ($g*0.95$ means that a true line width is assumed which is 0.95 times the line width assumed for the XCO₂ retrieval). All errors are shown as percentage errors (negative values correspond to an underestimation of the retrieved XCO₂) and as anomalies, i.e., the mean value of each curve has been subtracted to highlight the time (SZA) dependence of the potential retrieval error.

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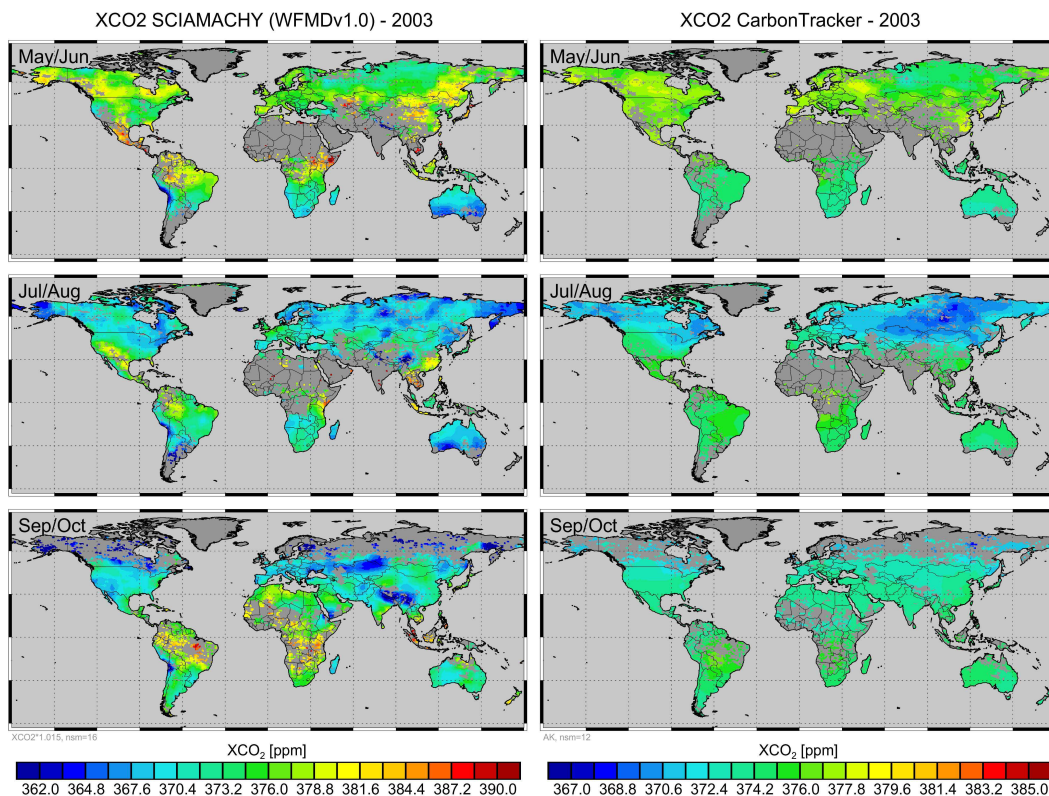


Fig. 13. Bi-monthly averages of the SCIAMACHY XCO₂ (left) compared to CarbonTracker (right). Shown are only those measurements for which the WFM-DOAS quality flag indicates a good measurement (see main text for details). The SCIAMACHY XCO₂ has been aerosol filtered. Note that different color scales have been used for SCIAMACHY (± 14 ppm) and CarbonTracker (± 9 ppm).

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USA & Canada (mid-west/east)

Lat: 25 to 60, Lon: -110 to -65

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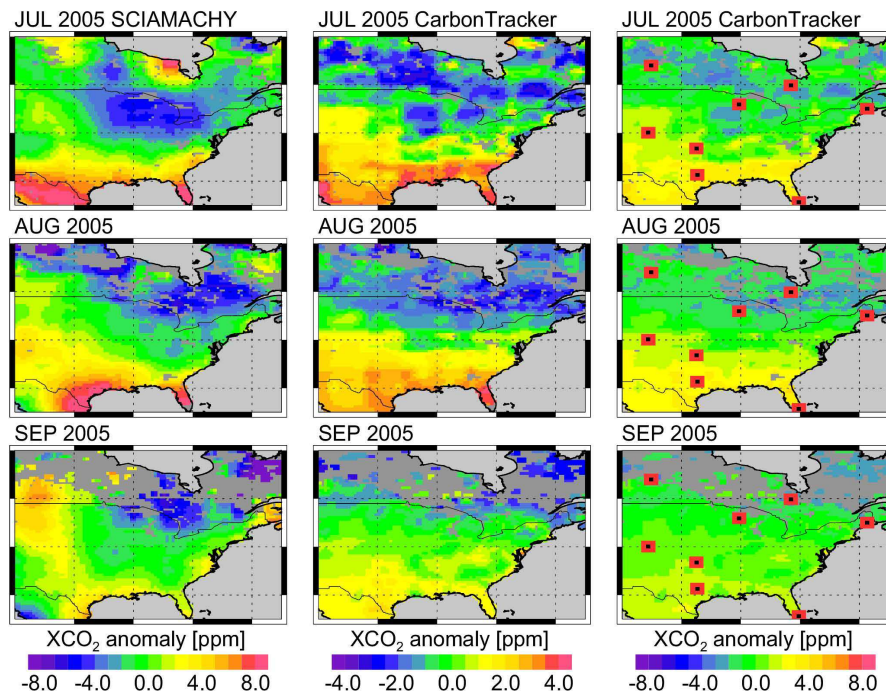


Fig. 14. The spatial pattern of XCO₂ over parts of the United States of America and Canada. The XCO₂ field is shown here as anomaly, i.e., the XCO₂ mean value has been subtracted for each panel. The first column shows the XCO₂ as retrieved from SCIAMACHY. The second column shows the CarbonTracker XCO₂ using an appropriate (different) color scale. The last column also shows the CarbonTracker XCO₂ but using the same color scale as has been used for the satellite data. The red rectangles indicate the spatial positions of observation sites used in CarbonTracker. The rows correspond to different months of the year 2005. The spatial resolution is 7° × 7°. The root mean square (RMS) differences between SCIAMACHY and CarbonTracker for the region shown are: July: 2.3 ppm (0.6%), August: 2.2 ppm (0.6%), and September: 2.9 ppm (0.8%).

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Europe, Asia & north-east Africa

Lat: 10 to 77, Lon: -10 to 130

ACPD

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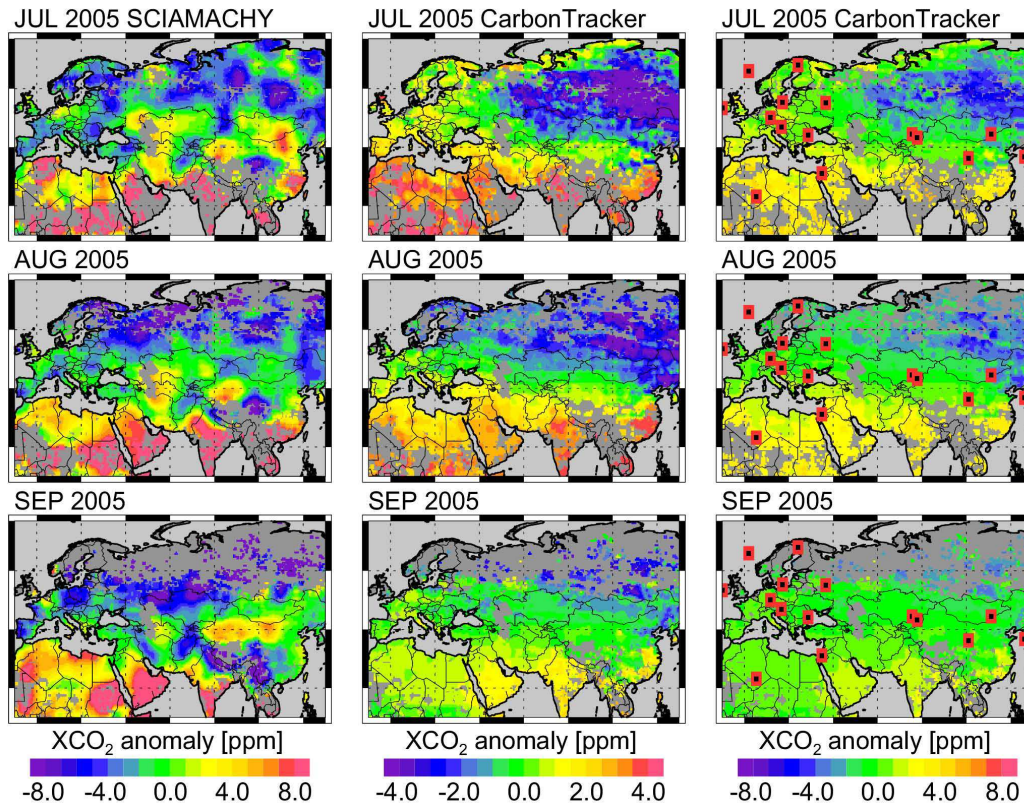


Fig. 15. As Fig. 14 but for Europe, Asia and parts of northern Africa. The RMS differences between SCIAMACHY and CarbonTracker for the region shown are: July: 4.3 ppm (1.2%), August: 4.0 ppm (1.1%), September: 5.0 ppm (1.3%).

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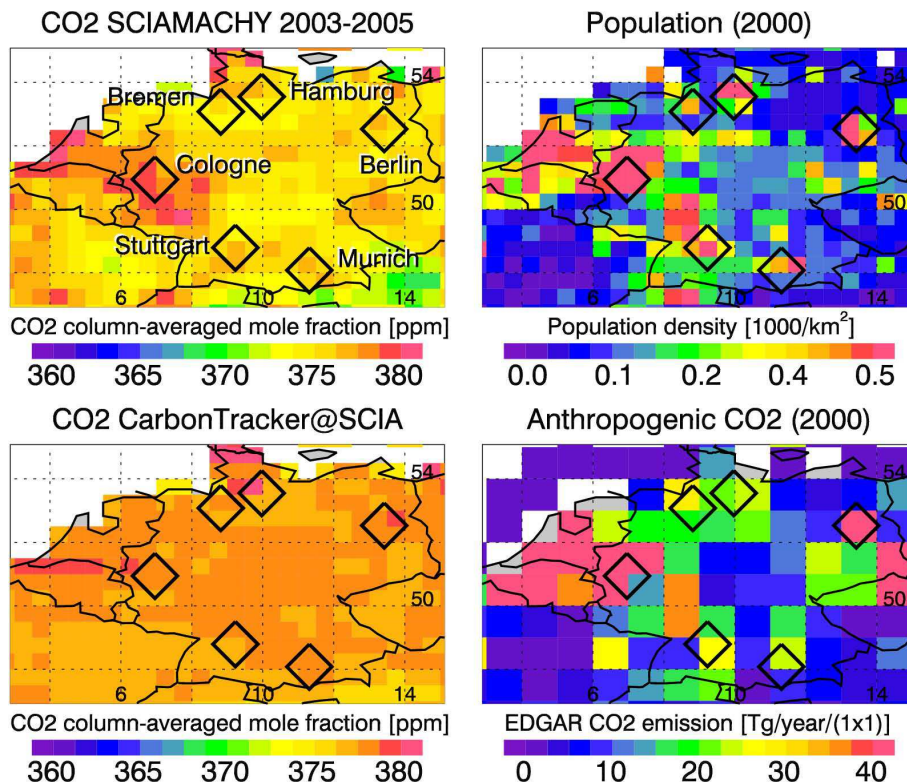


Fig. 16. SCIAMACHY XCO₂ over Germany (top left, 0.5°×0.5° gridded, scaled with 1.015) during 2003–2005 compared to population density (top right) (CIESIN/CIAT, 2005), anthropogenic CO₂ emissions (bottom right, EDGAR 32ft2000, 1°×1°) (Olivier et al., 2005), and CarbonTracker XCO₂ (bottom left, model resolution 4°×6° sampled as SCIAMACHY measures).

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