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First direct observation of the atmospheric CO_2 year-to-year increase from space

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Abstract. The reliable prediction of future atmospheric CO_2 concentrations and associated global climate change requires an adequate understanding of the CO_2 sources and sinks. The sparseness of the existing surface measurement network limits current knowledge about the global distribution of CO_2 surface fluxes. The retrieval of CO_2 total vertical columns from satellite observations is predicted to improve this situation. Such an application however requires very high accuracy and precision. We report on retrievals of the column-averaged CO_2 dry air mole fraction, denoted XCO_2, from the near-infrared nadir spectral radiance and solar irradiance measurements of the SCIAMACHY satellite instrument between 2003 and 2005. We focus on northern hemispheric large scale CO_2 features such as the CO_2 seasonal cycle and show - for the first time - that the atmospheric annual increase of CO_2 can be directly observed using satellite measurements of the CO_2 total column. The satellite retrievals are compared with global XCO_2 obtained from NOAA's CO_2 assimilation system CarbonTracker taking into account the spatio-temporal sampling and altitude sensitivity of the satellite data. We show that the measured CO_2 year-to-year increase agrees within about 1 ppm/year with CarbonTracker. We also show that the latitude dependent amplitude of the northern hemispheric CO_2 seasonal cycle agrees with CarbonTracker within about 2 ppm with the retrieved amplitude being systematically larger. The analysis demonstrates that it is possible using satellite measurements of the CO_2 total column to retrieve information on the atmospheric CO_2 on the level of a few parts per million.

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1 Introduction

Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas. In spite of the ratification of the Kyoto Protocol, the release of CO_2 is expected to continue to increase (IPCC, 2007). By using the very accurate and precise but sparse surface CO_2 measurements of the surface networks (e.g., the NOAA CMDL CCGG cooperative air sampling network, see www.esrl.noaa.gov/gmd/ccgg/), which comprises about 100 ground stations not equally distributed over the globe, inverse modeling has yielded surface fluxes of CO_2 globally by a variety of approaches (Gurney et al., 2002; Rödenbeck et al., 2003; Patra et al., 2006). These studies, which primarily used surface CO_2 data on a weekly basis, reveal that the inferred uncertainties of the CO_2 surface fluxes at the continental and ocean basin scale depend on many factors such as the a-priori assumptions made about the distribution of the CO_2 fluxes and their assumed uncertainties. In addition, attempts have been made for selected regions to better constrain the regional fluxes using continuous high-frequency CO_2 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 related to the required smoothness, the initial conditions, and the global flux field. Synthetic inverse modeling studies have suggested that satellite measurements of the column-averaged CO_2 dry air mole fraction, XCO_2, as possible using nadir measurements in the near-infrared spectral region, have the potential to significantly improve the determination of source/sink distributions of CO_2 (Rayner and O'Brien, 2001; Houweling et al., 2004). This results primarily from the large amounts of data that satellites produce, but also because nadir satellite remote sensing measurements in the near-infrared spectral region can observe the CO_2 molecules in the entire air column. As a result vertical transport modeling errors are less critical compared to inversions based on in-situ observations only.

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SCIAMACHY on ENVISAT (Burrows et al., 1995; Bovensmann et al., 1999) is the first satellite instrument, which makes the necessary observation of CO_2 and O_2 absorptions in the back scattered solar near-infrared (NIR) spectral regions (Buchwitz et al., 2005a,b, 2006). According to Rayner and O'Brien (2001) the precision, or random error, of the satellite measured XCO_2 is required to be less than approximately 2.5 ppm (0.7% of 375 ppm) for monthly averages and $8^\circ \times 10^\circ$ regions to constrain the CO_2 fluxes better than the surface network. Even more critical than random errors are potential systematic errors, as even a systematic error of less than 1 ppm between regions may be misinterpreted as a significant CO_2 source or sink (Chevallier et al., 2007; Miller et al., 2007). For the near future dedicated greenhouse gas satellite missions are planned, most notably OCO (Crisp et al., 2004) and GOSAT (Hamazaki et al., 2004), which will also perform passive nadir observations in the near-infrared spectral region but optimized for CO_2 in terms of, e.g., better spectral and spatial resolution. For GOSAT the required relative accuracy for sub-continental spatial resolution and 3-month XCO_2 averages is 1% or 4 ppm (Hamazaki et al., 2004).

Here we present three years (2003-2005) of SCIAMACHY XCO_2 retrievals. The XCO_2 has been retrieved using the latest version of our retrieval algorithm WFM-DOAS (version 1.0). Details about the algorithm are given in Schneising et al. (2007)[1]. Here we present a first discussion of the new multi year XCO_2 data set focusing on large scale CO_2 features over the northern hemisphere. We demonstrate, for the first time, that the about 1–3 ppm/year increase of the atmospheric CO_2, which primarily results from the burning of fossil fuels, can be directly observed from space. Indirectly, it been shown earlier by Aumann et al. (2005) that satellite measurements are sensitive enough to detect the CO_2 increase from space by analyzing AIRS middle to upper tropospheric temperature retrievals based on observations of the 4.3 micron CO_2 band. In that study it has been found that the retrieved temperature shows a decreasing trend because of the upward shift of the AIRS weighting functions with increasing CO_2, thereby sampling colder parts of the troposphere (because of the negative lapse rate) when CO_2 increases.

This paper is structured as follows: Sect. 2 gives a short overview about the SCIAMACHY satellite instrument. Section 3 introduces the XCO_2 retrieval algorithm. As not all the satellite XCO_2 measurements are useful, for example, due to clouds, the satellite retrieved XCO_2 must be filtered. This is described in Sect. 4. The main section of this paper is Sect. 5 where the XCO_2 data set is presented and discussed. Final conclusions are given in Sect. 6.

[1] Schneising, O., Buchwitz, M., Burrows, J. P., et al.: Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite – Part 1: Carbon dioxide, in preparation, 2007.

2 SCIAMACHY

The SCIAMACHY project (Burrows et al., 1995; Bovensmann et al., 1999) was intitiated in 1988 and is a German, Dutch and Belgian contribution to the ESA ENVISAT, which flies in a sun-synchronous orbit in descending node, crossing the equator at 10:00 a.m. local time. The SCIAMACHY instrument is a grating spectrometer, which measures solar radiation, reflected at the Earth's surface, backscattered from the atmosphere, transmitted through the atmosphere, or emitted from the atmosphere in the ultraviolet, visible, and NIR spectral regions (240–1750 nm, 1940–2040 nm, 2265–2380 nm) at moderate spectral resolution (0.2–1.4 nm). SCIAMACHY observes the Earth's atmosphere in various viewing geometries. Of relevance for this study is the nadir viewing mode (down-looking) and the 1558–1594 nm and 755–775 nm spectral regions containing molecular CO_2 and oxygen (O_2) absorption lines. The column-averaged dry air mole fraction of CO_2, XCO_2, is calculated from the retrieved columns of CO_2 and O_2 (Buchwitz et al., 2005a). The horizontal resolution, i.e., the size of a single ground pixel, is typically 30 km along track (approximately north-south) and 60 km across track (approximately east-west). On the Earth's day side an alternating sequence of nadir and limb measurements is performed. Full longitudinal (global) coverage in nadir is achieved at the equator in six days and more rapidly at higher latitudes. As shown in Buchwitz et al. (2005a), the sensitivity of the SCIAMACHY CO_2 measurements is only weakly dependent on altitude throughout the troposphere and down to the Earth's surface. The latter is a pre-requisite to obtain regional CO_2 source/sink information, which is the main scientific goal of the SCIAMACHY CO_2 measurements.

3 SCIAMACHY XCO_2 retrieval algorithm

Different groups have developed different algorithms to retrieve CO_2 columns or XCO_2 from the SCIAMACHY nadir spectra (e.g., Houweling et al. (2005); Barkley et al. (2006, 2007); Bösch et al. (2006)). We use the Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) method to retrieve the XCO_2 from SCIAMACHY as described in detail elsewhere (Buchwitz et al., 2000, 2005a,b, 2006). In short, WFM-DOAS is a least-squares method based fitting a linearized radiative transfer model plus a low-order polynomial to the logarithm of the measured sun-normalized radiance. The low order polynomial is included in the fit to account for not well known, ideally multiplicative, low frequency spectral radiance modulations, arising from residual radiometric calibration errors or (to first order, depending on optical thickness) radiance variability due to aerosols, residual clouds, and the surface spectral reflectivity. The fit parameters for the trace gases yield directly the vertical columns. The WFM-DOAS reference

spectra are the logarithm of the sun-normalized radiance and its derivatives, computed with a radiative transfer model taking into account multiple scattering.

The CO_2 column fit parameter is the relative deviation of the CO_2 vertical column from the atmospheric model vertical column assumed for the radiative transfer simulations. The assumed CO_2 vertical mixing ratio profile is constant (370 ppm) and this profile is converted to number density and scaled during the fitting procedure without changing the profile shape. For the results presented here it is important to point out that the retrieval algorithm has no knowledge about CO_2 variations in time and space. In order to convert the retrieved absolute CO_2 vertical column into XCO_2, the CO_2 column has to be divided by the corresponding dry air column. We obtain the dry air column using simultaneous measurements of molecular oxygen (O_2), assuming a constant mixing ratio of O_2 (0.2095). The CO_2 column is retrieved from the spectral region 1558–1594 nm located in the NIR part of the electromagnetic spectrum (sometimes also referred to as SWIR (shortwave infrared); note that this paper does not discriminate between NIR and SWIR), and the O_2 column is retrieved from the spectral region 755–775 nm (O_2 A-band).

The satellite XCO_2 year 2003–2005 data set presented here has been obtained with an improved version (version 1.0) of our retrieval algorithm WFM-DOAS (WFMDv1.0) (Schneising et al., 2007[1]). As will be shown in Schneising et al. (2007)[1] the main problems of the previous version WFMDv0.4 (Buchwitz et al., 2005a,b) have been solved by using better calibrated spectra (WFMDv1.0 uses the operational Level 1 version 5 data product instead of the previous Level 1 version 4 data product which has been used for WFMDv0.4; the Level 1 data product is the geolocated and spectrally and radiometrically calibrated (earthshine) spectral radiance and solar irradiance), a better consideration of surface spectral reflectivity variability, improved spectroscopic line parameters (HITRAN 2004 (Rothman et al., 2005) instead of HITRAN 2000/2001 (Rothman et al., 2003)), and by the implementation of several minor improvements. This resulted in higher accuracy of the retrieved XCO_2. For example, it is no longer required to apply a quite large empirical scaling factor as was necessary for WFMDv0.4 XCO_2.

4 Quality filtering of the SCIAMACHY XCO_2

Because of the demanding requirements on accuracy and precision, we have applied a stringent quality filter to the data shown here. As a result of this filtering, many measurements are currently rejected. The filtering (see below) removes most of the measurements at high latitudes and over the southern hemisphere, because the analysis of SCIAMACHY XCO_2 is restricted to cloud free and snow and ice free land surfaces. In this study we focus on northern hemispheric low and mid latitudes. For the future we will aim at further improving the retrieval algorithm to be able to relax the quality filtering in order to extend the XCO_2 data set.

The quality filtering approach is described in detail in Schneising et al. (2007)[1]. Here we restrict the description to a short overview. Quality flags marking successful measurements are set for each observed ground scene. For cloud detection, the measured oxygen columns and the sub-scene information provided by the SCIAMACHY Polarization Measurement Devices (PMDs) are used. A ground pixel is classified sufficiently cloud free if both, the PMD and the oxygen measurements indicate a cloud free pixel. In contrast to the oxygen measurements, the PMD threshold algorithm (Buchwitz et al., 2005a) can not not discriminate between clouds and snow or ice covered surfaces and therefore also rejects most of the measurements over snow or ice covered surfaces (snow and ice have low reflectivity in the near-infrared spectral region, therefore this results in the rejection of measurements with typically lower quality compared to typical snow and ice free land surfaces). With the exception of sun-glint conditions, water has a much lower surface spectral reflectance in the NIR spectral region than typical land surfaces, resulting in low signal-to-noise ratios of the SCIAMACHY nadir measurements in the NIR spectral region. Because of the lower quality of the CO_2 measurements over water, the analysis presented here is restricted to measurements over land. In addition, several criteria are employed to ensure a high significance and quality of the spectral fits. As the maximum ground altitude (pressure) currently considered for WFM-DOAS radiative transfer simulations of the nadir spectra is 4 km, we have also filtered out scenes corresponding to a surface elevation larger than 4.1 km. To reject ground scenes with strong aerosol contamination we have additionally filtered the SCIAMACHY XCO_2 measurements using NASA's Absorbing Aerosol Index (AAI) data product (Herman et al., 1997) from TOMS/Earthprobe.

5 Discussion of the XCO_2 data set

Figure 1 provides an overview about the northern hemispheric XCO_2 satellite data set. Shown are northern hemispheric monthly averages (square symbols) and annual averages (red horizontal lines). Clearly visible is the CO_2 year-to-year increase and the northern hemispheric seasonal cycle of CO_2, i.e., the regular once per year up and down of the atmospheric CO_2 due to uptake and release of CO_2 (primarily) by the terrestrial biosphere. Shown are also northern hemispheric maps obtained by sampling the seasonal cycle during its XCO_2 maximum and minimum time periods during the years 2003–2005. As can be seen, the satellite XCO_2 data set has spatial data gaps which change with time. They primarily result from the applied quality filter which may reject many measurements over extended areas for long time periods for example in case of significant aerosol contamination

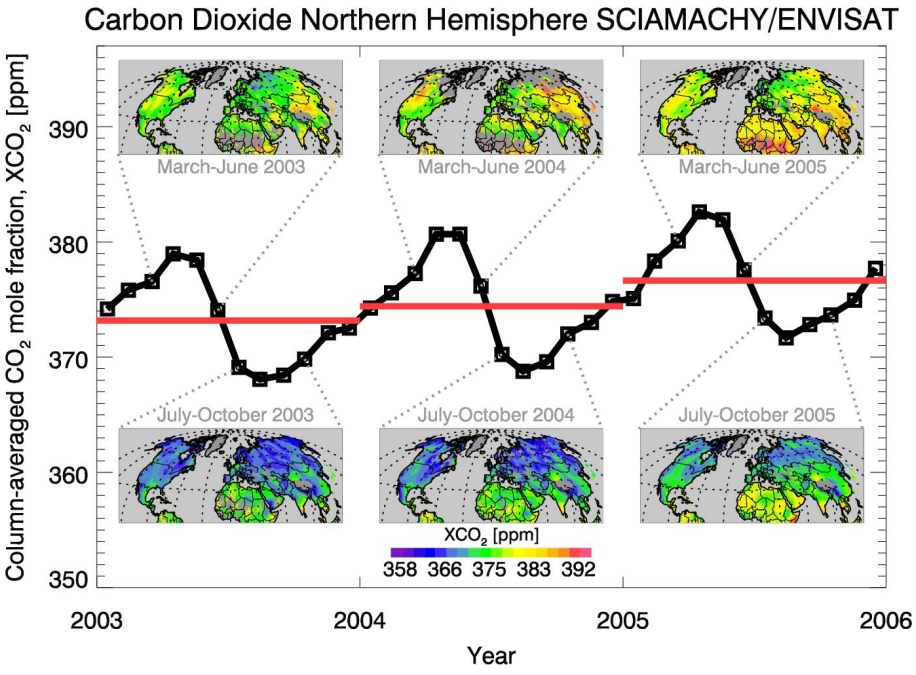

Fig. 1. Atmospheric CO_2 over the northern hemisphere during 2003-2005 as retrieved from SCIAMACHY satellite measurements. Shown is the column-averaged dry air mole fraction of CO_2, denoted XCO_2, in parts per million, ppm. The thick black curve shows the time dependence of the retrieved XCO_2 over the northern hemisphere in the time period 2003–2005 based on monthly averages (square symbols). Clearly visible is the seasonal cycle of CO_2 and its annual increase (the annual averages are shown as red horizontal lines). The maps show the spatial pattern of the retrieved XCO_2 over the northern hemisphere. For each map all quality filtered XCO_2 measurements within a 4 months time period have been averaged. The spatial resolution is $7° \times 7°$. The maps provide a visualization of the CO_2 "breathing" of our planet; here the term breathing refers to the regular uptake and release of CO_2 primarily by the terrestrial vegetation on a seasonal timescale, observed as higher than average March-June atmospheric CO_2 followed by lower than average July-October atmospheric CO_2.

in case of desert dust storms or due to persistent cloud coverage. Therefore, the monthly mean values shown in Fig. 1 are not averages representative for an average over all northern hemispheric land surfaces but suffer from a sampling error. The sampling of the satellite data has to be taken into account when the satellite retrievals are being compared with, for example, global model data (as done when discussing Fig. 2, see below). The satellite data shown in Fig. 1 have been scaled with 1.01 to compensate for an approximately 1% low bias as concluded from the comparison with ground-based Fourier Transform Spectroscopy (FTS) XCO_2 measurements (Schneising et al., 2007[1]).

In order to assess the quality of the retrieved XCO_2 we present in the following comparisons with independent reference data. Figure 2 shows a comparison of the retrieved XCO_2 with that determined from the global assimilation system CarbonTracker (Peters et al., 2007[2], see also http://carbontracker.noaa.gov) for two northern hemispheric latitude bands. CarbonTracker is a global assimilation system developed by NOAA ESRL in cooperation with many partners. CarbonTracker is a reanalysis of the recent global surface fluxes of carbon dioxide, as estimated from a large set of atmospheric CO_2 mole fractions produced via a data assimilation system. The CarbonTracker XCO_2 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 CO_2 column averaging kernels (Buchwitz et al., 2005a) to the CarbonTracker CO_2 vertical profiles. Concerning the accuracy of CarbonTracker, NOAA's comparison to about 14,000 independent aircraft 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 agreeement within typically ± 4 ppm).

Figure 2 shows monthly mean composite values of XCO_2 retrieved from SCIAMACHY, averaged over $\pm 20°$ latitude

[2]Peters, W., Jacobson, A. R., Sweeney, C., et al.: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, Proceedings of the National Academy of Sciences of the United States of America, submitted, 2007.

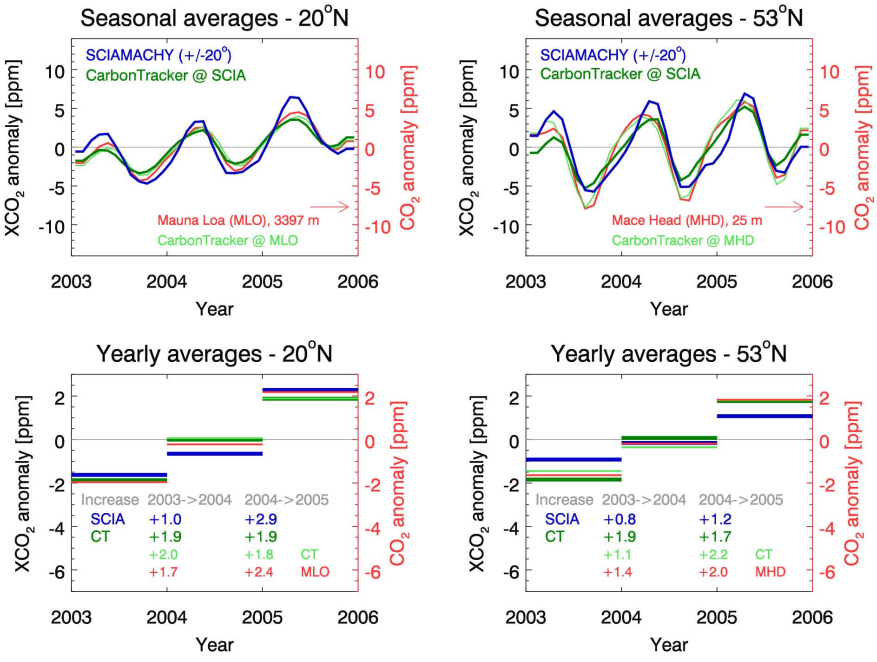

Fig. 2. Comparison between satellite and CarbonTracker XCO_2 for two latitude bands. The top panels show a comparison of seasonal averages (based on monthly mean anomalies smoothed using a 3 months running average). Shown is the retrieved XCO_2 (blue; left axis) and the CarbonTracker XCO_2 (dark green; left axis) for two latitude bands of width +/–20° centered at a latitude of 19.53° N corresponding to Mauna Loa, Hawaii, USA, (left) and a latitude of 53.33° N corresponding to Mace Head, Ireland (right). Also shown are the CO_2 measurements based on flask sampling (red; right axis) at the two stations Mauna Loa (MLO; latitude: 19.53° N, longitude: –155.58° E, altitude: 3397 m) and Mace Head (MHD; latitude: 53.33° N, longitude: –9.90° E, altitude: 25 m). Also shown are the local CarbonTracker results (light green, right axis) at the locations of the two ground stations. The bottom panels show the corresponding yearly mean anomalies as horizontal lines. For each data set the difference between two contiguous years has been computed (2004–2003 and 2005–2004) and the corresponding numbers are given in the bottom panels. They correspond to the year-to-year CO_2 increase in the corresponding latitude band (first two rows; for SCIAMACHY (blue) and CarbonTracker (dark green)) or locally at the two ground stations (last two rows; for the ground stations (red) and CarbonTracker (light green)).

bands, centerd at the latitudes of two selected ground based stations, namely Mauna Loa (20° N) and Mace Head (53° N). The average surface observations at the two stations, based on weekly flask sampling, are also shown (obtained from ftp://ftp.cmdl.noaa.gov/ccg/co2/flask/month/). The quantitative comparison of the surface observations and the satellite XCO_2 is not possible because of the different spatio-temporal sampling of the different types of measurements and retrievals resulting in different seasonal cycles with respect to phase and amplitude (Olsen et al., 2004; Warneke et al., 2005). A direct comparison of the satellite XCO_2 and the CarbonTracker XCO_2 is possible using the CarbonTracker results obtained by sampling and averaging CarbonTracker in the same way as the satellite observations. Within the two latitude bands, the phase of the XCO_2 seasonal cycle as retrieved from satellite and modelled by CarbonTracker is in good agreement. The retrieved amplitude of XCO_2 is however somewhat larger, especially in the latitude band centered at Mauna Loa. The surface observations and CarbonTracker show that the amplitude of the CO_2 seasonal cycle is larger at higher latitudes, i.e., at the latitude of Mace Head, 53° N, compared to the latitude of Mauna Loa, 20° N. This increase of the amplitude of the CO_2 seasonal cycle with increasing latitude is also observed by the satellite.

As shown in Buchwitz and Burrows (2004) the single measurement precision due to instrument noise is typically about 1% for SCIAMACHY XCO_2 measurements over land. In addition to instrument noise, also other errors contribute to the retrieval precision most notably variations of atmospheric and surface parameters which introduce additional retrieval noise. Based on the analysis of the SCIAMACHY XCO_2 at various locations we estimate this single measurement retrieval precision to about 1.5% for typical measurements over land (Schneising et al., 2007[1]). Here we discuss large scale features obtained from averaging large amounts of data. As the precision improves upon averaging, random errors are not a significant concern for the results discussed here in contrast to potential systematic errors which remain after averaging.

Several error sources contribute to the overall error. Concerning the error on the XCO_2 seasonal cycle, we have investigated in particular three error sources, namely errors due to the variability of atmospheric temperature, water vapour, and

CO_2 mixing ratio vertical profiles (Schneising et al., 2007[1]). A similar error analysis has been performed by Barkley et al. (2006) for SCIAMACHY WFM-DOAS CO_2 total column retrievals. Concerning these three error sources we find that the CO_2 profile variability error is the dominating one with an estimated amplitude of about 1.0–1.5 ppm. The time dependence of this error is significantly correlated with the XCO_2 seasonal cycle also showing a minimum around August. These findings are consistent with the results reported in Barkley et al. (2006). The CO_2 profile shape variability error may, therefore, explain a significant fraction of the differences with respect to CarbonTracker shown in Fig. 2. In addition, also aerosols and undetected clouds, e.g., sub-visual cirrus, result in errors of the retrieved XCO_2. As described, the satellite XCO_2 data set is filtered for clouds and strong aerosol contamination but some contamination will remain affecting the retrieval. Several studies have been performed to estimate aerosol and cloud related errors (e.g., Buchwitz and Burrows, 2004; Barkley et al., 2006; Aben et al., 2006). These studies focused on single measurement errors. Depending on the assumed scenario the errors cover a larger range from less than 1 ppm to up to several ppm, even if extreme cases are neglected.

To what extent these errors reduce when averaging large amounts of data is difficult to assess. Houweling et al. (2005), using several assumptions, have estimated the aerosol related SCIAMACHY CO_2 retrieval error that may results when one year of global data over the continents has been averaged and estimated this error to be 3 ppm. This value has been obtained by averaging over scenes with large errors (up to 10%), such as desert dust storms, which are filtered out for our study. Of relevance for this study would be to know to what extent these error sources affect the retrieved XCO_2 seasonal cycle and the year-to-year changes. To obtain an estimate of this seems hardly possible without introducing major assumptions. Therefore a reliable error estimate is currently not available. This also appears to be true for other error sources such as errors of the spectroscopic data. For example, the error on the air broadened line width of the strongest CO_2 lines used for the retrieval are 5–10% (Rothman et al., 2005) but this error is assumed to be mostly random. If however a certain fraction of this error would be systematic, a significant systematic error could be introduced which could be 1 ppm or larger and would also show a seasonal cycle as it depends on the solar zenith angle (Schneising et al., 2007[1]).

Because of the difficulty of obtaining a reliable independent end-to-end error estimate taking into account all potential error sources and their correlations, we estimate, at this stage, the error of the satellite retrievals using the comparison with the CarbonTracker reference data. The difference between the satellite retrievals and the Carbontracker XCO_2 can be interpreted as a conservative estimate of the systematic error of the satellite data as both, the satellite retrieval error and the CarbonTracker error, contribute to this difference. This interpretation requires that the CarbonTracker errors do not compensate the errors of the satellite data, which is very likely a realistic assumption.

From Fig. 2 one can see that the amplitudes of the retrieved seasonal cycles differs up to about 2 ppm from the amplitudes of the CarbonTracker data. Therefore, the error of the amplitude of the retrieved seasonal cycle should be less than about 2 ppm. How significant the systematically larger amplitude of the satellite retrievals compared to CarbonTracker is currently not clear. Such an assessment would require a reliable independent estimate of the error of the satellite retrievals, which is currently not available as explained above.

The annual CO_2 increase as retrieved from the satellite data shown in Fig. 2 is in reasonable agreement with CarbonTracker and similar to the increase observed by the two ground stations. The year-to-year increase depends on time an latitude and is between 1–3 ppm/year. From the comparison with CarbonTracker we conclude that the systematic error of the annual increase as obtained from the satellite data is less than about 1 ppm/year.

6 Conclusions

We have presented and discussed three years of satellite measurements of the column-averaged CO_2 dry air mole fraction, denoted XCO_2, retrieved from the SCIAMACHY instrument on board ENVISAT using the scientific retrieval algorithm WFM-DOAS version 1.0. The satellite retrievals have been compared with NOAA's global CO_2 assimilation system CarbonTracker. We have discussed several error sources which affect the retrieval but have not aimed at a full error analysis because of the challenge of reliably estimating the overall systematic errors which remain after averaging large amounts of data corresponding to many different conditions with several error sources and their correlations to be considered. Instead we interpret the differences with respect to the independent CarbonTracker reference data set as conservative estimates of the systematic error of the satellite retrievals.

We have shown, for the first time, that the CO_2 annual increase, which primarily results from the burning of fossil fuels (oil, coal, gas), can be observed from space. The retrieved CO_2 increase is, depending on time and latitude band, between 1–3 ppm/year. Based on the comparison with CarbonTracker we conclude that the year-to-year CO_2 changes can be determined with an accuracy of about 1 ppm/year. For two low and mid latitude bands over the northern hemisphere we have shown that the latitude dependent amplitude of the CO_2 seasonal cycle can be retrieved with an accuracy of better than about 2 ppm.

To what extent the satellite XCO_2 data set presented here is accurate enough to increase our knowledge about the carbon cycle still needs to be assessed. A very promising approach to assess this is the one used for methane by Bergamaschi et

al. (2007) based on inverse modeling which enables to investigate the consistency of data from various sources (e.g., surface, aircraft and satellite). The strength of column-averaged CO_2 measurements to increase our knowledge about the carbon cycle, and the difficulty in interpreting surface measurements in terms of surface fluxes using transport models which suffer from an imperfect parameterization of vertical mixing in the troposphere, has recently been shown in Yang et al. (2007). In that study it has been found that the seasonally varying northern hemispheric CO_2 fluxes appear to be substantially larger than assumed until now. Here we have shown that the amplitude of the CO_2 seasonal cycle as retrieved from the satellite data is systematically larger by about 1–2 ppm compared to CarbonTracker. Our error analysis indicates that this may be explained at least partially by assuming a constant CO_2 profile for the retrieval. To what extent the findings of Yang et al. (2007) also explain parts of the differences between the satellite data and CarbonTracker as shown here needs to be assessed.

In this study we have limited the discussion to large scale CO_2 features. The main objective of the satellite XCO_2 is to improve our knowledge about CO_2 fluxes on the regional scale. More details concerning the new WFM-DOAS version 1.0 retrieval algorithm and the XCO_2 year 2003 to 2005 data set, including regional details and a comparison with ground-based FTS XCO_2 measurements, will be presented elsewhere (e.g., in Schneising et al. (2007)[1]).

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