Atmos. Chem. Phys. Discuss., 7, 6719–6735, 2007
www.atmos-chem-phys-discuss.net/7/6719/2007/

Atmospheric Chemistry and Physics Discussions

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

M. Buchwitz, O. Schneising, J. P. Burrows, H. Bovensmann, and J. Notholt

Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany

Received: 13 April 200 – Accepted: 8 May 2007 – Published: 16 May 2007

Correspondence to: M. Buchwitz (michael.buchwitz@iup.physik.uni-bremen.de)

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 the CO_2 total vertical column from satellite observations is predicted to improve this situation. Such an application however requires very high accuracy and precision on the order of 1% (4 ppm) or better. We report on retrievals of the column-averaged CO_2 dry air mole fraction, denoted XCO_2, from the 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 the global assimilation system CarbonTracker and with local surface CO_2 measurements based on weekly flask sampling. We show that the year-to-year CO_2 increase as determined from the satellite data agrees with the reference data within about 1 ppm/year. We also show that the CO_2 seasonal cycle over northern hemispheric low and mid latitudes can be retrieved with a precision of about 2 ppm. The results presented here demonstrate that it is possible using satellite measurements to retrieved information on the atmospheric CO_2 on the level of a few parts per million.

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 precise but sparse in-situ CO_2 measurements of the surface network, which comprises about 100 ground stations not equally distributed over the globe, inverse modelling has yielded surface fluxes of CO_2 globally

ACPD

7, 6719–6735, 2007

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. Inverse modelling studies have suggested that satellite measurements of the column-averaged CO_2 dry air mole fraction, XCO_2, 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 can observe the CO_2 molecules in the entire air column. As a result vertical transport modelling errors are less critical compared to inversions based on in-situ observations only.

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) and short wave infrared (SWIR) 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. Probably even more critical than random errors are potential systematic errors, as even a small systematic error between regions may be misinterpreted as a large CO_2 source or sink. Currently no study exists where the acceptable bias between regions, or the relative accuracy, of the satellite XCO_2 measurements, has been specified without major assumptions. 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 perform similar measurements as SCIAMACHY, but optimised for CO_2. 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 focussing 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, this has been shown earlier by Aumann et al. (2005), analysing 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 part 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 satellite measurements of column-averaged dry air mole fractions of greenhouse gases – Part 1: Carbon dioxide, in preparation, 2007.

ACPD
7, 6719–6735, 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/SWIR 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 (nearly north-south) and 60 km across track (nearly east-west). On the Earth's dayside, 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 retrieved CO_2 columns or XCO_2 from the SCIAMACHY nadir spectra (e.g., Barkley et al., 2006, 2007; Bösch et al., 2006). We use the Weighting Function Modified Differential Optical Absorption Spec-

ACPD
7, 6719–6735, 2007

EGU

troscopy (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 radiance modulations arising from, e.g., aerosol scattering. 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. The results shown here are therefore free of any influence of a priori information about the spatio-temporal behaviour of CO_2. 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 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 SWIR part of the electromagnetic spectrum, 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 of our retrieval algorithm, WFM-DOAS version 1.0 (WFMDv1.0) (Schneising et al., 2007[1]). As shown in Schneising et al. (2007)[1] the main problems of the previous version WFMDv0.4 (Buchwitz et al., 2005a,b) have been solved primarily by using spectra with improved calibration (Level 1 data product version 5 instead of version 4), a better consideration of surface spectral reflectivity variability, 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 enhance 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. This approach (Buchwitz et al., 2005a) does not discriminate between clouds and snow or ice covered surfaces and therefore also rejects most of the measurements over snow or ice covered surfaces. With the exception of sun-glint conditions, water has a much lower surface spectral reflectance in the SWIR spectral region than typical land surfaces, resulting in low signal-to-noise ratios of the SCIAMACHY nadir measurements in the SWIR spectral region. Because of the lower quality of the CO_2 measurements over water, the analyses 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 (Houweling et al., 2005; Aben et al., 2006) we have additionally filtered the SCIAMACHY XCO_2 measurements using NASA's Absorbing Aerosol Index (AAI) data product from TOMS/Earthprobe.

5 Discussion of the XCO_2 data set

Figure 1 shows the retrieved XCO_2 over the northern hemisphere focusing on the seasonal cycle of CO_2, i.e., on 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 maps obtained by sampling the seasonal cycle during its XCO_2 maximum and minimum time periods during the years 2003–2005. Figure 1 also clearly shows that the retrieved XCO_2 is slowly increasing with time. A quantitative analysis of the satellite retrievals with reference data such as the global assimilation system CarbonTracker (see below) suggests that the satellite data have a quite systematic low bias of approximately 1% (Schneising et al., 2007[1]). To compensate for this, the XCO_2 shown in Fig. 1 has been scaled with 1.01.

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 SCIAMACHY 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

[2]Peters, W., Jacobson, A., Sweeneyet, C., et al.: The atmospheric perspective of carbondioxide exchange across North America: CarbonTracker, in preparation, 2007.

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.

Figure 2 shows monthly mean composite values of XCO_2 retrieved from SCIAMACHY, averaged over +/–20 degrees latitude bands, centred 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 averaging Carbon Tracker 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 centred at Mauna Loa, but within measurement error (see below). 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.

We have estimated the error of the retrieved XCO_2 seasonal cycle as shown in Fig. 2 to about 2 ppm. This error estimate has been obtained using two different independent approaches. Both approaches resulted in similar error estimates. The first approach is based on simulated retrievals, the second one is based on using the measurements directly. First we describe the approach based on simulations. Barkley et al. (2006) have performed an error analysis of the WFM-DOAS retrieval algorithm and found that errors are introduced for the measured CO_2 seasonal cycle if the variability of

atmospheric temperature, water vapour, and the CO_2 vertical profile, are imperfectly considered for the retrieval. They estimated the time dependent part of the error on the measured CO_2 column due to not perfectly accounted temperature and water vapour profile variability to be less than 0.6% peak to peak, corresponding to an error of the amplitude of less than 0.3%. These estimates are valid if the solar zenith angle is less than 75° and if temperature and water vapour profile scaling and shift parameters are included in the WFM-DOAS CO_2 column fit, as done for this study. For XCO_2 this corresponds to an error of the amplitude of the seasonal cycle of less than 1.2 ppm (0.3% of 375 ppm). Concerning the error resulting from CO_2 vertical profile variability, Barkley et al. (2006) using a set of CO_2 vertical profiles, estimated the error that results if a constant CO_2 profile is used for the retrieval, as is the case for the results presented here. They found that this may result in an error of less than 0.9% peak to peak, for mid latitudes and the tropics, corresponding to an error of the amplitude of less than 0.45%. For XCO_2 this corresponds to an error of less than 1.7 ppm. Both errors contribute to the total measurement error. In the worst case, assuming that all errors simply add linearly and without any compensation, and assuming that the time dependence of the combined error is perfectly correlated with the CO_2 seasonal cycle, which is not exactly the case (see, Barkley et al., 2006), this results in an error of the amplitude of the measured CO_2 seasonal cycle of less than 2.9 ppm (1.2 ppm + 1.7 ppm), i.e., less than 0.8%. This error is dominated by the CO_2 vertical profile variability error. The findings of Barkley et al. (2006) are consistent with our own error analysis (Schneising et al., 2007[1]).

The second approach to estimate the seasonal cycle measurement error is not based on simulations but is based on analysing the retrieved XCO_2 over the southern and the northern hemisphere. Over southern hemispheric mid latitudes the retrieved seasonal cycle has an amplitude of about 5 ppm (Schneising et al., 2007[1]) whereas the amplitude of the seasonal cycle of CarbonTracker is only about 1–3 ppm. For the year 2003 we have analysed the XCO_2 difference (DIF), SCIAMACHY minus CarbonTracker, as a function of the air mass factor, AMF (here geometrically defined

as AMF = 1/cos(SZA) + 1/cos(LOS), where SZA is the solar zenith angle at the time of the satellite measurement and LOS is the line-of-sight scan angle of SCIAMACHY). When plotting DIF versus AMF we found a reasonable linear dependence which can be described by DIF = a+b*AMF. For southern hemispheric mid latitudes we found a = 23 ppm and b = –12 ppm with the dimensionless AMF varying between 2.3 (begin and end of 2003) to 2.9 (mid 2003). We repeated this analysis not using CarbonTracker but assuming a constant XCO_2 value of 373 ppm. This resulted in nearly exactly the same coefficients a and b. We have applied this potential correction to the retrievals over the northern hemisphere but found that this results in a seasonal cycle significantly out of phase by about 2 months, compared to the seasonal cycle shown in Fig. 2. From this we conclude that such as correction is too strong. We confirmed this by repeating this analysis for northern hemispheric mid latitudes. Here we obtained a = 10 ppm and b = –5 ppm (somewhat depending on spatial region). The error bar shown in Fig. 2 has been generated assuming an AMF (or SZA) dependent error that can be described by 10-5*AMF ppm. In addition, we have enhanced the error bar by 1 ppm to both sides. This error bar, which is shown in Fig. 2, is similar as the independently determined error bar obtained from the analysis of the simulated retrievals as described above.

As also shown in Fig. 2, the annual CO_2 increase, measured by the satellite, is in reasonable agreement with CarbonTracker and similar to the increase observed by the two ground stations, being on the order of 1–3 ppm/year. Figure 2 shows, for the first time, that it is possible to observe the long-term increase of CO_2 from space. From the comparison with CarbonTracker and the surface CO_2 measurements one can conclude that the precision of the retrieved year-to-year increase is 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 retrieved from the SCIAMACHY instrument using the retrieval algorithm WFM-DOAS version 1.0. The satellite retrievals have been

compared with NOAA's global assimilation system CarbonTracker. We have shown that the CO_2 seasonal cycle over northern hemispheric low and mid latitudes can be retrieved with a precision of about 2 ppm. We have also shown, for the first time, that the year-to-year CO_2 increase, which primarily results from the burning of fossil fuels, can be observed from space. Based on the comparison with CarbonTracker and the highly precise NOAA surface CO_2 measurements obtained from weekly flask sampling we estimate the retrieval precision of the XCO_2 increase to about 1 ppm/year. In this manuscript we have focused on demonstrating that the annual increase of atmospheric CO_2 can be observed from space. More details concerning the new WFM-DOAS version 1.0 retrieval algorithm and the XCO_2 year 2003 to 2005 data set will be presented elsewhere (e.g., in Schneising et al., 2007[1]).

Acknowledgements. We thank ESA and DLR for providing us with the SCIAMACHY Level 1 data. We appreciate the availability of CarbonTracker results from http://carbontracker.noaa.gov and comments on the initial manuscript from W. Peters and P. Tans from NOAA/ESRL/GMD. We thank T. J. Conway and colleagues, also NOAA/ESRL/GMD, for the CO_2 surface measurements (obtained from ftp://ftp.cmdl.noaa.gov/ccg/co2/flask/month/). We also thank P. Wennberg (Caltech, Pasadena, California, USA) for the suggestion to investigte the dependence of the difference between SCIAMACHY and CarbonTracker XCO_2 over the southern hemisphere as a function of the airmass factor. The SCIAMACHY XCO_2 has been filtered for strong aerosol contamination using TOMS/Earthprobe Absorbing Aerosol Index (AAI) data product obtained from NASA/GSFC, which has been produced by the TOMS Ozone Processing Team (OPT). Funding for this study came from the German Ministry for Research and Education (BMBF) via DLR-Bonn (projects 50EE0027 and 50EE0507), from ESA (GSE project PROMOTE) and from the University and the State of Bremen. We acknowledge exchange of information within the European Commission Network of Excellence ACCENT.

References

Aben, I., Hasekamp, O., and Hartmann, W.: Uncertainties in the space-based measurements of CO_2 columns due to scattering in the Earth's atmosphere, J. Quant. Spectrosc. Rad.

Transfer, 104, 450–459, 2006. 6726
Aumann, H. H., Gregorich, D., and Gaiser, S.: AIRS hyper-spectral measurements for climate research: Carbon dioxide and nitrous oxide effects, Geophys. Res. Lett., 32, L05806, doi:10.1029/2004GL021784, 2005. 6722
Barkley, M. P., Frieß, U. and Monks, P. S.: Measuring atmospheric CO_2 from space using full spectral initiation (FSI) WFM-DOAS, Atmos. Chem. Phys., 6, 3517–3534, 2006, http://www.atmos-chem-phys.net/6/3517/2006/. 6723, 6727, 6728
Barkley, M. P., Monks, P. S., Hewitt, A. J., Machida, T., Desai, A., Vinnichenko, N., Nakazawa, T., Yu Arshinov, M., Fedoseev, N., and Watai, T.: Assessing the near surface sensitivity of SCIAMACHY atmospheric CO_2 retrieved using (FSI) WFM-DOAS, Atmos. Chem. Phys. Discuss., 7, 2477–2530, 2007, http://www.atmos-chem-phys-discuss.net/7/2477/2007/. 6723
Bösch, H., Toon, G. C., Sen, B., Washenfelder, R. A., Wennberg, P. O., Buchwitz, M., de Beek, R., Burrows, J. P., Crisp, D., Christi, M., Connor, B. J., Natraj, V., and Yung, Y. L.: Space-based near-infrared CO_2 measurements: Testing the Orbiting Carbon Observatory retrieval algorithm and validation concept using SCIAMACHY observations over Park Falls, Wisconsin, J. Geophys. Res., 111, D23302, doi:10.1029/2006JD007080, 2006. 6723
Bovensmann, H., Burrows, J. P., Buchwitz, M., Frerick, J., Noël, S., Rozanov, V. V., Chance, K. V., and Goede, A.: SCIAMACHY – Mission Objectives and Measurement Modes, J. Atmos. Sci., 56, 127–150, 1999. 6721, 6723
Buchwitz, M., Rozanov, V. V., and Burrows, J. P.: A near infrared optimized DOAS method for the fast global retrieval of atmospheric CH_4, CO, CO_2, H_2O, and N_2O total column amounts from SCIAMACHY/ENVISAT-1 nadir radiances, J. Geophys. Res., 105, 15 231–15 246, 2000. 6724
Buchwitz, M., de Beek, R., Burrows, J. P., Bovensmann, H., Warneke, T., Notholt, J., Meirink, J. F., Goede, A. P. H., Bergamaschi, P., Körner, S., Heimann, M., and Schulz, A.: Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: Initial comparison with chemistry and transport models, Atmos. Chem. Phys., 5, 941–962, 2005a. 6721, 6723, 6724, 6725, 6727
Buchwitz, M., de Beek, R., Noël, S., Burrows, J. P., Bovensmann, H., Bremer, H., Bergamaschi, P., Körner, S., and Heimann, M.: Carbon monoxide, methane, and carbon dioxide retrieved from SCIAMACHY by WFM-DOAS: year 2003 initial data set, Atmos. Chem. Phys., 5, 3313–3329, 2005b. 6721, 6724

Buchwitz, M., de Beek, R., Noël, S., Burrows, J. P., Bovensmann, H., Schneising, O., Khlystova, I., Bruns, M., Bremer, H., Bergamaschi, P., Körner, S., and Heimann, M.: Atmospheric carbon gases retrieved from SCIAMACHY by WFM-DOAS: version 0.5 CO and CH_4 and impact of calibration improvements on CO_2 retrieval, Atmos. Chem. Phys., 6, 2727–2751, 2006, http://www.atmos-chem-phys.net/6/2727/2006/. 6721, 6724

Burrows, J. P., Hölzle, E., Goede, A. P. H., Visser H., and Fricke, W., SCIAMACHY – Scanning Imaging Absorption Spectrometer for Atmospheric Chartography, Acta Astronautica, 35(7), 445–451, 1995. 6721, 6723

Crisp, D., Atlas, R. M., Breon, F.-M., Brown, L. R., Burrows, J. P., Ciais, P., Connor, B. J., Doney, S. C., Fung, I. Y., Jacob, D. J., Miller, C. E., O'Brien, D., Pawson, S., Randerson, J. T., Rayner, P., Salawitch, R. S., Sander, S. P., Sen, B., Stephens, G. L., Tans, P. P., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Yung, Y. L., Kuang, Z., Chudasama, B., Sprague, G., Weiss, P., Pollock, R., Kenyon, D., and Schroll, S.: The Orbiting Carbon Observatory (OCO) mission, Adv. Space Res., 34, 700–709, 2004. 6722

Derwent, R. G., Ryall, D. B., Manning, A. J., Simmonds, P. G., ODoherty, S., Biraud, S., Ciais, P., Ramonet, M., and Jennings, S. G., Continuous observations of carbon dioxide at Mace Head, Ireland from 1995 to 1999 and its net European ecosystem exchange, Atmos. Environ., 36, 2799–2807, 2002. 6721

Gurney, K. R., Rachel M. Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fan, S., Fung, I. Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Maki, T., Maksyutov, S., Masarie, K., Peylin, P., Michael Prather, M., Pak, B. C., Randerson, J., Jorge Sarmiento, J., Shoichi Taguchi, S., Takahashi, T., Yuen, C.-W.: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models, Nature, 415, 626–630, 2002. 6721

Hamazaki, T., Kaneko, Y., and Kuze, A., Carbon dioxide monitoring from the GOSAT satellite, Proceedings XXth ISPRS conference, Istanbul, Turkey, 12–23 July 2004, p.3, http://www.isprs.org/istanbul2004/comm7/papers/43.pdf, 2004. 6722

Houweling, S., Breon, F.-M., Aben, I., Rödenbeck, C., Gloor, M., Heimann, M., and Ciais, P.: Inverse modeling of CO_2 sources and sinks using satellite data: A synthetic inter-comparison of measurement techniques and their performance as a function of space and time, Atmos. Chem. Phys., 4, 523–538, 2004, http://www.atmos-chem-phys.net/4/523/2004/. 6721

Houweling, S., Hartmann, W., Aben, I., Schrijver, H., Skidmore, J., Roelofs, G.-J., and Breon,

F.-M.: Evidence of systematic errors in SCIAMACHY-observed CO_2 due to aerosols, Atmos. Chem. Phys., 5, 3003–3013, 2005, http://www.atmos-chem-phys.net/5/3003/2005/. 6726

IPCC, Alley, R., Berntsen, T., Bindoff, N. L., et al., (drafting authors), Climate change 2007: The physical basis - Summary for policy makers, Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), IPCC web page (http://www.ipcc.ch/SPM2feb07.pdf), 2007. 6720

Olsen, S. C., and Randerson, J. T.: Differences between surface and column atmospheric CO_2 and implications for carbon cycle research, J. Geophys. Res., 109, D02301, doi:10.1029/2003JD003968, 2004. 6727

Patra, P. K., Gurney, K. R., Denning, A. S. Maksyutov, S., Nakazawa, T., Baker, D. Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fan, S., Fung, I., Gloor, M., Heimann, M., Higuchi, K., John, L., Law, R. M., Maki, T., Pak, B. C., Peylin, P., Prather, M., Rayner, P. J., Sarmiento, J., Taguchi, S., Takahashi, T., and Yuen, C.-W.: Sensitivity of inverse estimation of annual mean CO_2 sources and sinks to ocean-only sites versus all-sites observational networks, Geophys. Res. Lett., 33, L05814, doi:10.1029/2005GL025403, 2006. 6721

Peylin, P., Rayner, P. J., Bousquet, P., Carouge, C., Hourdin, F., Heinrich, P., Ciais, P., and AEROCARB contributors: Daily CO_2 flux estimates over Europe from continuous atmospheric measurements: 1, inverse methodology, Atmos. Chem. Phys., 5, 3173–3186, 2005, http://www.atmos-chem-phys.net/5/3173/2005/. 6721

Rayner, P. J. and O'Brien, D. M.: The utility of remotely sensed CO_2 concentration data in surface inversions, Geophys. Res. Lett., 28, 175–178, 2001. 6721

Rödenbeck, C., Houweling, S., Gloor, M., and Heimann, M.: CO_2 flux history 1982–2001 inferred from atmospheric data using a global inversion of atmospheric transport, Atmos. Chem. Phys., 3, 1919–1964, 2003, http://www.atmos-chem-phys.net/3/1919/2003/. 6721

Warneke, T., Yang, Z., Olsen, S., Körner, S., Notholt, J., Toon, G. C., Velazco, V., Schulz, A., and Schrems, O.: Seasonal and latitudinal variations of columns averaged volume-mixing ratios of atmospheric CO_2, Geophys. Res. Lett., 32, L03808, doi:10.1029/2004GL021597, 2005. 6727

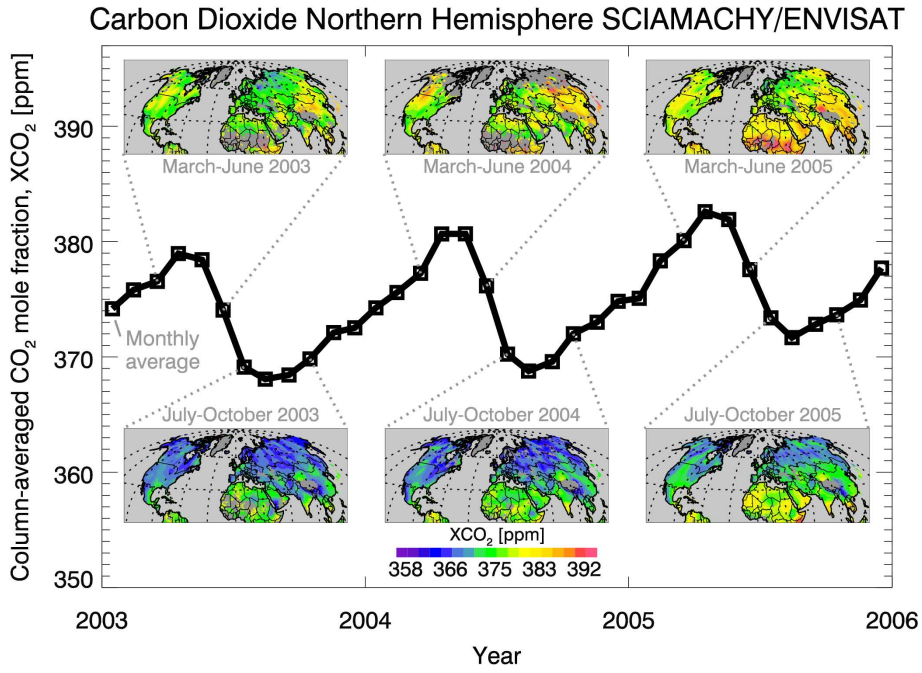

Fig. 1. Atmospheric CO_2 over the northern hemisphere during 2003–2005 as retrieved from SCIAMACHY satellite measurements. Shown is the column-averaged dry air mole fraction of CO_2, denoted XCO_2, in parts per million, ppm. The thick black curve shows the time dependence of the retrieved XCO_2 over the northern hemisphere in the time period 2003–2005 based on monthly averages (square symbols). Clearyl visible is the seasonal cylcle of CO_2 and its annual increase. 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 periode have been averaged. The spatial resolution is $7^{\circ} \times 7^{\circ}$. 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.

ACPD
7, 6719–6735, 2007

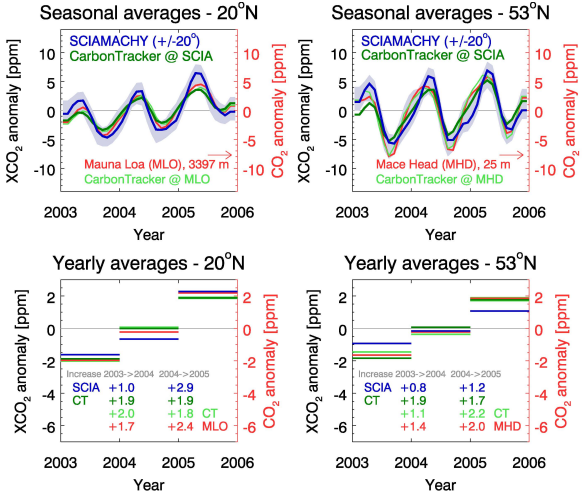

Fig. 2. Comparison between satellite and CarbonTracker XCO_2 for two latitude bands. The top panels show a comparison of seasonal averages (based on monthly mean anomalies smoothed using a 3 months running average). Shown is the retrieved XCO_2 (blue; left axis) and the CarbonTracker XCO_2 (dark green; left axis) for two latitude bands of width +/–20° centred 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). For the SCIAMACHY XCO_2 the estimated error of the retrieved seasonal cycle is shown as light blue shaded area (see main text for details). 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)).

ACPD
7, 6719–6735, 2007