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M. Buchwitz, O. Schneising, J. P. Burrows, H. Bovensmann, J. Notholt. First direct observation of the atmospheric CO₂ year-to-year increase from space. *Atmospheric Chemistry and Physics Discussions*, 2007, 7 (3), pp.6719-6735. hal-00302786

HAL Id: hal-00302786

<https://hal.science/hal-00302786>

Submitted on 18 Jun 2008

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**First direct
observation of CO₂
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M. Buchwitz et al.

First direct observation of the atmospheric CO₂ year-to-year increase from space

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

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

The reliable prediction of future atmospheric CO₂ concentrations and associated global climate change requires an adequate understanding of the CO₂ sources and sinks. The sparseness of the existing surface measurement network limits current knowledge about the global distribution of CO₂ surface fluxes. The retrieval of the CO₂ 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 CO₂ dry air mole fraction, denoted XCO₂, from the measurements of the SCIAMACHY satellite instrument between 2003 and 2005. We focus on northern hemispheric large scale CO₂ features such as the CO₂ seasonal cycle and show – for the first time – that the atmospheric annual increase of CO₂ can be directly observed using satellite measurements of the CO₂ total column. The satellite retrievals are compared with the global assimilation system CarbonTracker and with local surface CO₂ measurements based on weekly flask sampling. We show that the year-to-year CO₂ increase as determined from the satellite data agrees with the reference data within about 1 ppm/year. We also show that the CO₂ 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 retrieve information on the atmospheric CO₂ on the level of a few parts per million.

1 Introduction

Carbon dioxide (CO₂) is the most important anthropogenic greenhouse gas. In spite of the ratification of the Kyoto Protocol, the release of CO₂ is expected to continue to increase (IPCC, 2007). By using the precise but sparse in-situ CO₂ measurements of the surface network, which comprises about 100 ground stations not equally distributed over the globe, inverse modelling has yielded surface fluxes of CO₂ globally

First direct observation of CO₂ increase from space

M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

by a variety of approaches (Gurney et al., 2002; Rödenbeck et al., 2003; Patra et al., 2006). These studies, which primarily used surface CO₂ data on a weekly basis, reveal that the inferred uncertainties of the CO₂ 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 CO₂ fluxes and their assumed uncertainties. 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 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 CO₂ dry air mole fraction, XCO₂, have the potential to significantly improve the determination of source sink distributions of CO₂ (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 CO₂ 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 CO₂ and O₂ 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 XCO₂ is required to be less than approximately 2.5 ppm (0.7% of 375 ppm) for monthly averages and 8° × 10° regions to constrain the CO₂ 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 CO₂ source or sink. Currently no study exists where the acceptable bias between regions, or the relative accuracy, of the satellite XCO₂ measurements, has been specified without major assumptions. For the near future dedicated greenhouse gas satellite missions are planned,

**First direct
observation of CO₂
increase from space**M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

most notably OCO (Crisp et al., 2004) and GOSAT (Hamazaki et al., 2004), which will perform similar measurements as SCIAMACHY, but optimised for CO₂. For GOSAT the required relative accuracy for sub-continental spatial resolution and 3-month XCO₂ averages is 1% or 4 ppm (Hamazaki et al., 2004).

Here we present three years (2003-2005) of SCIAMACHY XCO₂ retrievals. The XCO₂ 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 XCO₂ data set focussing on large scale CO₂ features over the northern hemisphere. We demonstrate, for the first time, that the about 1–3 ppm/year increase of the atmospheric CO₂, 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 CO₂ 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 CO₂, thereby sampling colder parts of the troposphere (because of the negative lapse rate) when CO₂ increases.

This paper is structured as follows: Sect. 2 gives a short overview about the SCIAMACHY satellite instrument. Section 3 introduces the XCO₂ retrieval algorithm. As not all the satellite XCO₂ measurements are useful, for example, due to clouds, the satellite retrieved XCO₂ must be filtered. This is described in Sect. 4. The main part of this paper is Sect. 5 where the XCO₂ data set is presented and discussed. Final conclusions are given in Sect. 6.

¹Schneising, 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.

**First direct
observation of CO₂
increase from space**M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2 SCIAMACHY

The SCIAMACHY project (Burrows et al., 1995; Bovensmann et al., 1999) was initiated 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 CO₂ and oxygen (O₂) absorption lines. The column-averaged dry air mole fraction of CO₂, XCO₂, is calculated from the retrieved columns of CO₂ and O₂ (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 CO₂ 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 CO₂ source/sink information, which is the main scientific goal of the SCIAMACHY CO₂ measurements.

3 SCIAMACHY XCO₂ retrieval algorithm

Different groups have developed different algorithms to retrieve CO₂ columns or XCO₂ 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-

**First direct
observation of CO₂
increase from space**

M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

5 troscopy (WFM-DOAS) method to retrieve the XCO₂ 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

10 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.

15 The CO₂ column fit parameter is the relative deviation of the CO₂ vertical column from the atmospheric model vertical column assumed for the radiative transfer simulations. The assumed CO₂ 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

20 that the retrieval algorithm has no knowledge about CO₂ 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 CO₂. In order to convert the retrieved absolute CO₂ vertical column into XCO₂, the CO₂ column has to be divided by the corresponding dry air column. We obtain the dry air using simultaneous measurements of molecular oxygen (O₂), assuming a constant mixing ratio of O₂ (0.2095). The CO₂ column is retrieved from the spectral region 1558–1594 nm located in the SWIR part of the electromagnetic spectrum, and the O₂ column is retrieved from the spectral region 755–775 nm (O₂ A-band).

25 The satellite XCO₂ 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., 2007¹). 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

**First direct
observation of CO₂
increase from space**M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

implementation of several minor improvements. This resulted in higher accuracy of the retrieved XCO₂. For example, it is no longer required to apply a quite large empirical scaling factor as was necessary for WFMDv0.4 XCO₂.

4 Quality filtering of the SCIAMACHY XCO₂

5 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 XCO₂ is restricted to cloud free and snow and ice free land surfaces. 10 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 XCO₂ 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 CO₂ measurements over water, the analyses presented here is restricted to measurements over land. In addition, several criteria are employed to 20 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

**First direct
observation of CO₂
increase from space**

M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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 XCO₂ measurements using NASA's Absorbing Aerosol Index (AAI) data product from TOMS/Earthprobe.

5 Discussion of the XCO₂ data set

Figure 1 shows the retrieved XCO₂ over the northern hemisphere focusing on the seasonal cycle of CO₂, i.e., on the regular once per year up and down of the atmospheric CO₂ due to uptake and release of CO₂ primarily by the terrestrial biosphere. Shown are also maps obtained by sampling the seasonal cycle during its XCO₂ maximum and minimum time periods during the years 2003–2005. Figure 1 also clearly shows that the retrieved XCO₂ 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., 2007¹). To compensate for this, the XCO₂ shown in Fig. 1 has been scaled with 1.01.

In order to assess the quality of the retrieved XCO₂ we present in the following comparisons with independent reference data. Figure 2 shows a comparison of SCIAMACHY retrieved XCO₂ with that determined from the global assimilation system CarbonTracker (Peters et al., 2007², 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 CO₂ mole fractions produced via a data assimilation system. The CarbonTracker XCO₂ field as used for this study has been sampled in space and time as the

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

First direct observation of CO₂ increase from space

M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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.

Figure 2 shows monthly mean composite values of XCO₂ 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 XCO₂ 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 XCO₂ and the CarbonTracker XCO₂ 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 XCO₂ seasonal cycle as retrieved from satellite and modelled by CarbonTracker is in good agreement. The retrieved amplitude of XCO₂ 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 CO₂ 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 CO₂ seasonal cycle with increasing latitude is also observed by the satellite.

We have estimated the error of the retrieved XCO₂ 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 CO₂ seasonal cycle if the variability of

**First direct
observation of CO₂
increase from space**M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

atmospheric temperature, water vapour, and the CO₂ vertical profile, are imperfectly considered for the retrieval. They estimated the time dependent part of the error on the measured CO₂ 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 CO₂ column fit, as done for this study. For XCO₂ 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 CO₂ vertical profile variability, Barkley et al. (2006) using a set of CO₂ vertical profiles, estimated the error that results if a constant CO₂ 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 XCO₂ 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 CO₂ seasonal cycle, which is not exactly the case (see, Barkley et al., 2006), this results in an error of the amplitude of the measured CO₂ 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 CO₂ vertical profile variability error. The findings of Barkley et al. (2006) are consistent with our own error analysis (Schneising et al., 2007¹).

The second approach to estimate the seasonal cycle measurement error is not based on simulations but is based on analysing the retrieved XCO₂ 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., 2007¹) whereas the amplitude of the seasonal cycle of CarbonTracker is only about 1–3 ppm. For the year 2003 we have analysed the XCO₂ difference (DIF), SCIAMACHY minus CarbonTracker, as a function of the air mass factor, AMF (here geometrically defined

**First direct
observation of CO₂
increase from space**M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**First direct
observation of CO₂
increase from space**

M. Buchwitz et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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 XCO₂ 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 a 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 CO₂ 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 CO₂ from space. From the comparison with CarbonTracker and the surface CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ measurements obtained from weekly flask sampling we estimate the retrieval precision of the XCO₂ increase to about 1 ppm/year. In this manuscript we have focused on demonstrating that the annual increase of atmospheric CO₂ can be observed from space. More details concerning the new WFM-DOAS version 1.0 retrieval algorithm and the XCO₂ year 2003 to 2005 data set will be presented elsewhere (e.g., in Schneising et al., 2007¹).

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 CO₂ 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 investigate the dependence of the difference between SCIAMACHY and CarbonTracker XCO₂ over the southern hemisphere as a function of the airmass factor. The SCIAMACHY XCO₂ 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.

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**First direct
observation of CO₂
increase from space**

M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Transfer, 104, 450–459, 2006. [6726](#)
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**First direct
observation of CO₂
increase from space**M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**First direct
observation of CO₂
increase from space**M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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ACPD

7, 6719–6735, 2007

**First direct
observation of CO₂
increase from space**

M. Buchwitz et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Carbon Dioxide Northern Hemisphere SCIAMACHY/ENVISAT

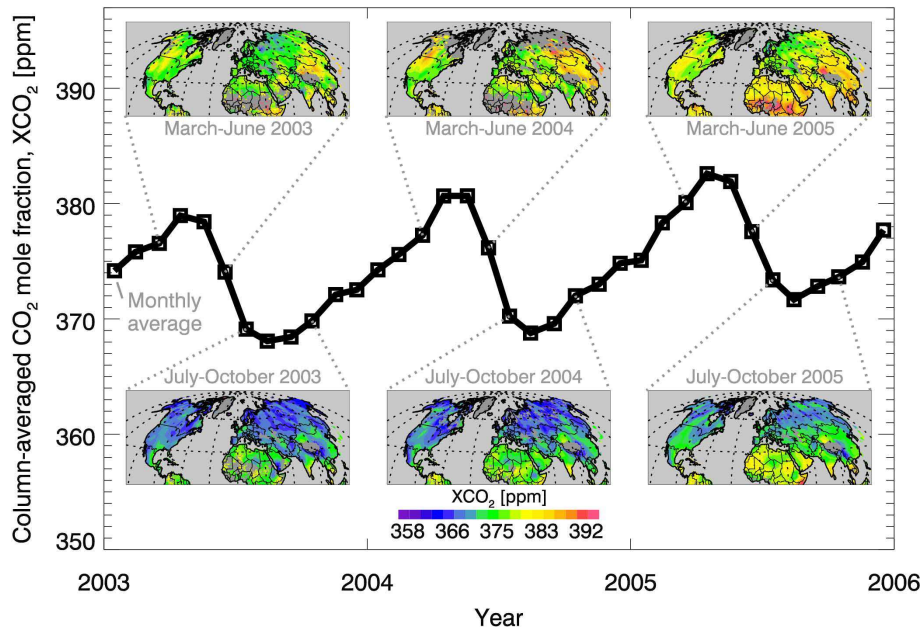


Fig. 1. Atmospheric CO₂ over the northern hemisphere during 2003–2005 as retrieved from SCIAMACHY satellite measurements. Shown is the column-averaged dry air mole fraction of CO₂, denoted XCO₂, in parts per million, ppm. The thick black curve shows the time dependence of the retrieved XCO₂ over the northern hemisphere in the time period 2003–2005 based on monthly averages (square symbols). Clearly visible is the seasonal cycle of CO₂ and its annual increase. The maps show the spatial pattern of the retrieved XCO₂ over the northern hemisphere. For each map all quality filtered XCO₂ measurements within a 4 months time period have been averaged. The spatial resolution is 7° × 7°. The maps provide a visualization of the CO₂ “breathing” of our planet; here the term breathing refers to the regular uptake and release of CO₂ primarily by the terrestrial vegetation on a seasonal timescale, observed as higher than average March-June atmospheric CO₂ followed by lower than average July-October atmospheric CO₂.

First direct observation of CO₂ increase from space

M. Buchwitz et al.

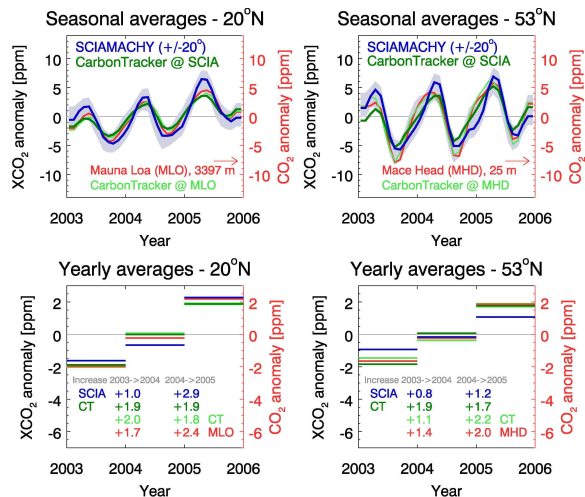


Fig. 2. Comparison between satellite and CarbonTracker XCO₂ for two latitude bands. The top panels show a comparison of seasonal averages (based on monthly mean anomalies smoothed using a 3 months running average). Shown is the retrieved XCO₂ (blue; left axis) and the CarbonTracker XCO₂ (dark green; 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 XCO₂ the estimated error of the retrieved seasonal cycle is shown as light blue shaded area (see main text for details). Also shown are the CO₂ 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 CO₂ 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)).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion