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Consistent satellite XCO_2 retrievals from SCIAMACHY and GOSAT using the BESD algorithm

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AMTD

8, 1787–1832, 2015

SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.

Abstract

Consistent and accurate long-term data sets of global atmospheric concentrations of carbon dioxide (CO_2) are required for carbon cycle and climate related research. However, global data sets based on satellite observations may suffer from inconsistencies originating from the use of products derived from different satellites as needed to cover a long enough time period. One reason for inconsistencies can be the use of different retrieval algorithms. We address this potential issue by applying the same algorithm, the Bremen Optimal Estimation DOAS (BESD) algorithm, to different satellite instruments, SCIAMACHY onboard ENVISAT (March 2002–April 2012) and TANSO-FTS onboard GOSAT (launched in January 2009), to retrieve XCO_2, the column-averaged dry-air mole fraction of CO_2. BESD has been initially developed for SCIAMACHY XCO_2 retrievals. Here, we present the first detailed assessment of the new GOSAT BESD XCO_2 product. GOSAT BESD XCO_2 is a product generated and delivered to the MACC project for assimilation into ECMWF's Integrated Forecasting System (IFS). We describe the modifications of the BESD algorithm needed in order to retrieve XCO_2 from GOSAT and present detailed comparisons with ground-based observations of XCO_2 from the Total Carbon Column Observing Network (TCCON). We discuss detailed comparison results between all three XCO_2 data sets (SCIAMACHY, GOSAT and TCCON). The comparison results demonstrate the good consistency between the SCIAMACHY and the GOSAT XCO_2. For example, we found a mean difference for daily averages of -0.60 ± 1.56 ppm (mean difference ± standard deviation) for GOSAT-SCIAMACHY (linear correlation coefficient $r = 0.82$), -0.34 ± 1.37 ppm ($r = 0.86$) for GOSAT-TCCON and 0.10 ± 1.79 ppm ($r = 0.75$) for SCIAMACHY-TCCON. The remaining differences between GOSAT and SCIAMACHY are likely due to non-perfect collocation (±2 h, $10° \times 10°$ around TCCON sites), i.e., the observed air masses are not exactly identical, but likely also due to a still non-perfect BESD retrieval algorithm, which will be continuously improved in the future. Our overarching goal is to generate a satellite-derived XCO_2 data set appropriate for climate and carbon cycle research covering the longest

possible time period. We therefore also plan to extend the existing SCIAMACHY and GOSAT data set discussed here by using also data from other missions (e.g., OCO-2, GOSAT-2, CarbonSat) in the future.

1 Introduction

Space-based observations of carbon dioxide (CO_2) can contribute to eliminate important knowledge gaps related to the regional sources and sinks of CO_2 (Rayner and O'Brien, 2001; Hungershoefer et al., 2010; Schneising et al., 2013, 2014; Reuter et al., 2014b, c). Near-surface sensitive measurements of column-averaged dry-air mole fractions of CO_2 (XCO_2) in the short-wave infrared spectral region (SWIR) are well suited for this application. These observations can complement measurements from existing surface-based greenhouse gas monitoring networks, especially in data-poor regions, by providing data with dense spatial coverage. However, satellite measurements need to be precise and accurate enough to reduce uncertainties in the characterization of the sources and sinks. Studies showed that a precision of better than 1 % for regional averages and monthly means (Rayner and O'Brien, 2001; Houweling et al., 2004) and regional biases of less than a few tenth of a part per million (ppm) are required (Chevallier et al., 2007; Miller et al., 2007).

The SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) onboard the European Space Agency's (ESA) Environmental Satellite (ENVISAT) (Burrows et al., 1995; Bovensmann et al., 1999), launched in 2002, was in the time period before mid 2009 the only satellite instrument measuring XCO_2 with high surface sensitivity. The long-term time series of surface-sensitive satellite-derived XCO_2 starts with SCIAMACHY. SCIAMACHY had observed the Earth's atmosphere till the loss of ENVISAT in April 2012.

The Thermal And Near infrared Sensor for carbon Observations Fourier Transform Spectrometer (TANSO-FTS) onboard the Greenhouse gases Observing SATellite (GOSAT) (Kuze et al., 2009), launched in January 2009, and the Orbiting Carbon

Observatory-2 (OCO-2) (Crisp et al., 2004), launched in July 2014, are currently the only satellite instruments yielding XCO_2 with high near-surface sensitivity. Both satellite missions are specifically designed to observe XCO_2.

Several retrieval algorithms have been developed to evaluate the satellite observations for SCIAMACHY (e.g., Schneising et al., 2012; Heymann et al., 2012b; Reuter et al., 2011) and for GOSAT (e.g., Yoshida et al., 2013; Crisp et al., 2012; Guerlet et al., 2013; Cogan et al., 2012; Oshchepkov et al., 2008). These algorithms differ in, e.g., cloud and aerosol treatment, state vector elements and cloud filtering (for more details see, e.g., Reuter et al., 2013; Takagi et al., 2014). One of these algorithms is the Bremen Optimal Estimation DOAS (BESD) retrieval algorithm developed for the evaluation of SCIAMACHY measurements at the University of Bremen (Reuter et al., 2010, 2011). As unaccounted scattering by aerosols and clouds is a major error source for satellite retrievals (e.g., Aben et al., 2006; Houweling et al., 2005; Heymann et al., 2012a; Guerlet et al., 2013), BESD aims to reduce this error source by explicitly considering atmospheric scattering (Reuter et al., 2010). The BESD algorithm has been used to generate a SCIAMACHY XCO_2 data product ranging from 2002–2012. This data product has been used in several key European projects, e.g., ESA's Climate Change Initiative (CCI, www.esa-ghg-cci.org and Buchwitz et al., 2013b; Hollmann et al., 2013) and the EU's Monitoring of Atmospheric Composition and Climate (MACC, Hollingsworth et al., 2008) project.

Carbon cycle and climate related research requires consistent and accurate long-term global CO_2 datasets. However, global data sets based on observations from different satellite instruments may suffer from inconsistencies originating from the use of different satellite algorithms. We address this potential issue by applying the same retrieval algorithm, the BESD algorithm, to different satellite instruments, SCIAMACHY and TANSO-FTS. Within the European MACC project, after the loss of ENVISAT, the BESD algorithm has been modified to also retrieve XCO_2 from TANSO-FTS measurements. The GOSAT/TANSO-FTS BESD XCO_2 product was delivered for the assimilation into ECMWF's Integrated Forecasting System (IFS) (Agustí-Panareda et al., 2014).

Here, we report first results of an assessment of the new GOSAT BESD XCO_2 data product. In addition, we discuss results of an investigation concerning the consistency of the SCIAMACHY BESD and GOSAT BESD XCO_2 data sets. This analysis includes a comparison of validation results obtained by using data from the Total Carbon Column Observing Network (TCCON, Wunch et al., 2011a) and a direct comparison of daily satellite-based XCO_2 data.

This paper is structured as follows: in Sects. 2 and 3, relevant aspects of the SCIAMACHY and TANSO-FTS instruments are discussed. Section 4 gives a short overview of the SCIAMACHY BESD retrieval algorithm whereas in Sect. 5 the recently developed GOSAT BESD XCO_2 retrieval algorithm is introduced. This includes the GOSAT Level 1c generation (fully calibrated total intensity, measurement error and a priori information), the GOSAT Level 2 XCO_2 generation as well as the cloud filtering and post processing. In Sect. 6 the comparison of the satellite XCO_2 data with TCCON is described and discussed. Finally, conclusions are given in Sect. 7.

2 SCIAMACHY on ENVISAT

The satellite instrument SCIAMACHY (Burrows et al., 1995; Bovensmann et al., 1999) was part of the atmospheric chemistry payload on-board ESA's ENVISAT. The ENVISAT satellite was launched in March 2002. On 8 April 2012, after 10 years of operation, ESA lost contact to ENVISAT and finally had decided the official end of the ENVISAT mission on 9 May 2012. ENVISAT flew on a sun-synchronous daytime (descending) orbit with an equator crossing time of 10 a.m. (LT).

The SCIAMACHY instrument was a passive remote sensing moderate–resolution imaging spectrometer and measured sunlight transmitted, reflected and scattered by the earth's atmosphere or surface in the ultraviolet, visible and near-infrared wavelength regions in eight spectral channels (214–1750, 1940–2040, 2265–2380 nm) with a spectral resolution between 0.2–1.4 nm. The scientific objective of SCIAMACHY was to improve our knowledge of global atmospheric change and related issues of impor-

AMTD
8, 1787–1832, 2015

tance to the chemistry and physics of the atmosphere, i.e., the impact of pollution, exchange processes between atmospheric layers, atmospheric chemistry in polar and other regions and the influence of natural phenomena such as volcanic eruptions. Targets of SCIAMACHY were atmospheric gases (e.g. O_3, NO_2, CH_4 and CO_2) as well as clouds and aerosols, ocean colour and land parameters. SCIAMACHY measured in three different viewing geometries: nadir, limb and solar/lunar occultation.

For the work presented in this study the nadir mode observations in channel 4 (755–775 nm) and channel 6 (1558–1594 nm) has been used. The integration time of the instrument in the used spectral regions was typically 0.25 s. This provided a typical spatial resolution of ~ 60 km across track and ~ 30 km along track. By scanning ±32° across track, SCIAMACHY achieved a swath width of ~ 1000 km.

3 TANSO-FTS on GOSAT

GOSAT has been the first satellite mission dedicated to measure atmospheric XCO_2 and XCH_4 (Kuze et al., 2009). GOSAT is a joint project of the Japanese Aerospace Exploration Agency (JAXA), the National Institute for Environmental Studies (NIES) and the Ministry of the Environment (MOE). The objectives of GOSAT are to monitor the global distribution of greenhouse gases, to estimate CO_2 and CH_4 sources and sinks on subcontinental scale and to verify reductions of anthropogenic greenhouse gas emissions (Kuze et al., 2009). On 23 January 2009, GOSAT was launched in a sun-synchronous daytime orbit with an equator crossing time of 1 p.m. (LT).

GOSAT carries two satellite instruments, the TANSO-FTS and the Cloud and Aerosol Imager (TANSO-CAI). The TANSO-FTS is a double pendulum interferometer. It measures two orthogonal polarization directions of reflected or scattered sunlight in three bands (band 1, 2, 3) in the SWIR between 4800 and 13 200 cm^{-1} (758–2083 nm). In addition to the SWIR bands, band 4 measures in the thermal infrared between 700 and 1800 cm^{-1} (5.56–14.3 µm). However, measurements obtained with band 4 are not considered in this paper. TANSO-FTS has a spectral resolution of $\Delta\nu_1 \approx 0.36\ cm^{-1}$

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD
8, 1787–1832, 2015

SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.

($\Delta\lambda_1 \approx 0.02$ nm) in band 1 and $\Delta\nu_{2,3} \approx 0.26$ cm^{-1} ($\Delta\lambda_2 \approx 0.07$ nm and $\Delta\lambda_3 \approx 0.1$ nm) in bands 2 and 3. In order to improve the dynamic range of the instrument, TANSO-FTS can measure in three gain modes, low (L), medium (M) and high (H), used according to the measured level of intensity. For example, Gain M is used over bright surfaces such as deserts. With an instantaneous field of view (IFOV) of 15.8 mrad ($\sim$ 10.5 km diameter at nadir when projected to the ground), TANSO-FTS can measure ±35° across track and ±20° along track. The typically used scan time of one interferogram is 4 s. Between 4 April 2009 and 31 July 2010, the 5-point across track mode was used, which yields footprints separated by $\sim$ 158 km across track and $\sim$ 152 km along track at the equator (e.g., Crisp et al., 2012). In order to improve the pointing stability during the scans, on 1 August 2010, the observation mode was changed to a 3-point across track mode with footprints separated by $\sim$ 263 km across track and $\sim$ 283 km along track at the equator.

The TANSO-CAI instrument is a high spatial resolution imager detecting clouds and optically thick aerosol layers within the TANSO-FTS field of view. The TANSO-CAI data products are not used for the BESD algorithm.

4 SCIAMACHY BESD algorithm

The BESD retrieval algorithm has been developed at the University of Bremen to retrieve XCO_2 from SCIAMACHY nadir measurements. BESD aims to minimize scattering related errors of the retrieved XCO_2. For this purpose, the algorithm explicitly accounts for scattering. The theoretical basis of BESD and a study of synthetic retrievals is presented in the publication of Reuter et al. (2010) and validation results are presented in Reuter et al. (2011).

The algorithm is a core algorithm within ESA's Climate Change Initiative (CCI) (Hollmann et al., 2013; Buchwitz et al., 2013b; Dils et al., 2014) aiming at delivering high quality satellite retrievals. Here we use the most recent product version (02.00.08) of SCIAMACHY BESD, which is part of the Climate Research Data Package (CRDP#2) of the CCI project. A detailed description of the current version of BESD can be found in the Algorithm Theoretical Basis Document (ATBD) (Reuter et al., 2014a, available at http://www.esa-ghg-cci.org/). Here, only a short overview of the algorithm is given.

The BESD algorithm retrieves several independent parameters from the O_2-A band (755–775 nm) in SCIAMACHY's channel 4 and from a CO_2 band (1558–1594 nm) in channel 6. An optimal estimation based inversion technique is used to derive the most probable atmospheric state from a SCIAMACHY measurement using some a priori knowledge. The state vector consists of 26 elements. These elements include a wavelength shift and the full width half maximum (FWHM) of a Gaussian shaped instrumental slit function, both are fitted separately in the O_2 and CO_2 fit window. A Lambertian surface albedo with smooth spectral progression expressed as a 2nd order polynomial (with polynomial coefficients P_0, P_1 and P_2) is fitted separately in both fit windows. A ten-layered CO_2 mixing ratio profile, which is separated in equally spaced pressure intervals, is fitted in the CO_2 fit window. The correlated a priori errors of the CO_2 profile layers provide a degree of freedom of the retrieved XCO_2 of ~ 1.0. Re-analysis profiles (ERA-Interim, Dee et al., 2011) of pressure, temperature and humidity provided by the European Centre for Medium-range Weather Forecasts (ECMWF) are used for the forward model calculation needed to calculate simulated SCIAMACHY spectra. The surface pressure, a shift of the temperature profile and the H_2O column averaged mole fraction are fitted in the O_2 and CO_2 window simultaneously.

Atmospheric scattering is considered by fitting three scattering related parameters. A thin ice cloud layer consisting of fractal ice crystals with 50 µm effective radius and a thickness of 0.5 km is defined for the forward model calculations. Within the retrieval, the cloud water path (CWP) and the cloud top height (CTH) are retrieved. Aerosols are considered by using a standard LOWTRAN summer aerosol profile with moderate rural aerosol load. A Henyey–Greenstein phase function is used and the total optical thickness is about 0.136 at 750 nm and 0.038 at 1550 nm. The aerosol retrieval is based on scaling the pre-defined aerosol profile (aerosol profile scaling factor APS). The scattering parameters but also the parameters defining the meteorological situation are fitted

AMTD
8, 1787–1832, 2015
SCIAMACHY and GOSAT BESD XCO_2 retrievals
J. Heymann et al.

simultaneously via a merged fit window approach. Simultaneous fitting in both fit windows transfers, e.g., in case of scattering parameters, information mostly obtained from the O_2-A band to the CO_2 band.

The forward model is the radiative transfer model SCIATRAN (Rozanov et al., 2014). SCIATRAN calculates the needed radiance spectra and weighting functions, which are the derivatives of the measured radiation. The correlated-k approach of Buchwitz et al. (2000) is used to accelerate the radiative transfer calculations. Line parameters from NASA's absorption cross section database ABSCO v4.0 (Thompson et al., 2012) is used for O_2. The HITRAN 2008 database (Rothman et al., 2009) are used for the other gases. The calculated spectra are convolved with a Gaussian slit function.

Although BESD has been designed to minimise scattering related retrieval errors, clouds are still an important potential error source and strict cloud filtering is necessary. BESD filters clouds by using cloud information based on measurements of the Medium Resolution Imaging Spectrometer (MERIS).

The post-processing of the retrieved data includes strict quality filtering and an empirical bias correction. This is needed due to the demanding accuracy requirements on the satellite retrievals. The implemented bias correction for SCIAMACHY BESD is described in the BESD ATBD (Reuter et al., 2014a).

5 GOSAT BESD algorithm

The GOSAT BESD algorithm is based on the SCIAMACHY BESD algorithm which has been modified to also retrieve XCO_2 from GOSAT. Here, an overview of the modifications of BESD are given.

5.1 Level 1c data generation

GOSAT BESD uses GOSAT Level 1b data (L1b) version 161160. These data have been obtained from the GOSAT User Interface Gateway (GUIG) (http://data.gosat.nies.

go.jp/GosatUserInterfaceGateway/guig/GuigPage/open.do) and from ESA's GOSAT Third Party Mission (TPM) data archive. The (uncalibrated) L1b data has been converted into calibrated Level 1c (L1c) data by using, e.g., the radiance correction scheme described by Yoshida et al. (2012). The L1c data consists of the fully calibrated total intensity, an estimation of the measurement error and a priori information. The total intensity is computed by using the polarisation synthesis method described by Yoshida et al. (2011) using the Mueller Matrices described by Kuze et al. (2009). The measurement noise ($\varepsilon_{\text{meas}}$) is estimated by the standard deviation of the first 500 and the last 500 off-band spectral points of GOSAT bands 1, 2 and 3. These spectral points lie outside the band pass filter and can therefore provide a good estimate of $\varepsilon_{\text{meas}}$. However, using only the estimate of the measurement noise for the retrieval neglects the contribution of the forward model error. Therefore, empirical noise ($\varepsilon_{\text{empirical}}$) has been implemented and used as described by Yoshida et al. (2013) and Crisp et al. (2012). In order to account for the forward model error, we make the same assumptions as done by Yoshida et al. (2013). We assume that our forward model error increases as the signal to noise ratio (SNR) increases. Using the same formula as given by Yoshida et al. (2013)

$$\varepsilon_{\text{empirical}} = \varepsilon_{\text{meas}} \cdot \sqrt{a_0 + a_1 \text{SNR} + a_2 \text{SNR}^2} \quad (1)$$

and evaluate the relationship between SNR and the mean squared values of the residual spectra delivers the coefficients a_0, a_1 and a_2 in each spectral window. The coefficients are listed in Table 1.

The a priori information includes profiles of temperature, pressure and humidity obtained from ECMWF data and height information from a digital elevation model (DEM). The used DEM (obtained from http://www.viewfinderpanoramas.org) is mostly based on data collected in 2000 by the Shuttle Radar Topography Mission (SRTM) and has a spatial resolution of 15 arc s. A priori estimates for the 0th order polynomial coefficient of the albedo (P_0) are obtained by computing the 95 % percentile of the reflectance (sun-normalised GOSAT intensity divided by the cosine of the solar zenith angle).

AMTD
8, 1787–1832, 2015

5.2 GOSAT XCO_2 (Level 2) generation

The GOSAT XCO_2 (Level 2) data have been generated by using a modified version of the SCIAMACHY BESD retrieval algorithm. The main modifications are the following:

we have used three bands instead of two bands (as used for SCIAMACHY) for the retrieval of GOSAT XCO_2. Band 1 includes the O_2-A band (12 920–13 195 cm^{-1} or 758–774 nm), band 2 contains a weak CO_2 absorption band (6170–6278 cm^{-1} or 1593–1621 nm) and band 3 includes a strong CO_2 absorption band (4804–4896 cm^{-1} or 2042–2082 nm).

The state vector of GOSAT BESD consists of 38 elements instead of 26 for SCIAMACHY BESD. The state vector elements, their a priori values and uncertainties are listed in Table 2. A 2nd order albedo polynomial is additionally fitted in the third fit window. Besides a spectral shift of the nadir radiance, a shift of the solar spectrum is fitted. Instead of the FWHM of a SCIAMACHY Gaussian slit function, parameters defining the Instrumental Line Shape Function (ILS) of TANSO-FTS are fitted. These parameters are the Maximum Optical Path Difference (MOPD) and the Instantaneous Field Of View (IFOV). The ILS is calculated (similar as done by, e.g., Reuter et al., 2012a) from

$$\mathrm{ILS}(\nu) \propto \Pi\left(\frac{8\nu}{\nu_0 \mathrm{IFOV}}\right) \otimes \mathrm{sinc}(2\nu \cdot \mathrm{MOPD}). \quad (2)$$

Here, ν is the wavenumber (centred around zero), Π is a boxcar function, the "$\otimes$" is the convolution operator and ν_0 is the centre wavenumber.

A temperature shift, the column averaged mole fraction of water vapour and the surface pressure are fitted as for SCIAMACHY BESD and also the CO_2 profile consists of 10 layers. The CO_2 a priori profile is obtained by using the Simple Empirical CO_2 Model (SECM) described by Reuter et al. (2012b). The a priori uncertainty of the CO_2 profile has been scaled (similar to Reuter et al., 2010) so that the a priori XCO_2 uncertainty is about 42 ppm. This large value enables that the XCO_2 retrieval is virtually unconstrained.

AMTD
8, 1787–1832, 2015

Contributions from plant fluorescence and the impact of a non-linearity response of the incident radiation to the intensity in the mostly affected band 1 can be reduced by fitting a wavenumber independent offset (also called zero-level offset) (Butz et al., 2011). This has also been implemented in GOSAT BESD for the O_2-A band.

The fit parameters defining atmospheric scattering are the same as for SCIAMACHY BESD, namely CWP, CTH and APS. The defined thin cloud layer consists of fractal ice particles with an effective radius of 100 µm.

The much higher spectral resolution of GOSAT is the reason why the radiative transfer model SCIATRAN cannot run in the implemented computational efficient correlated-k mode used for SCIAMACHY BESD. However, in order to accelerate the radiative transfer calculations for GOSAT BESD retrievals, tabulated cross sections (based on the absorption cross sections database ABSCO v4.0 described by Thompson et al., 2012) have been used and the linear-k scheme of Hilker (2015) has been implemented. A high spectral resolution solar irradiance spectrum based on the "OCO TOON spectrum" (O'Dell et al., 2012) is used to calculate the total intensity instead of the sun-normalised intensity as used by SCIAMACHY BESD. The simulated intensity is convolved with the GOSAT ILS (Eq. 2).

In Fig. 1 a typical example of observed and fitted GOSAT spectra in all three fitting windows is presented. The observed and fitted spectra show reasonable agreement. The reduced χ^2 (computed as described by Yoshida et al., 2013) is in all three fitting windows ~ 1 which means that the difference between observed and fitted spectra agrees with the estimated noise.

5.3 Cloud filtering and post processing

Even thin clouds are a main error source for satellite XCO_2 retrievals. Therefore, GOSAT BESD includes a cloud detection method similar to Yoshida et al. (2011) and Heymann et al. (2012b). The intensity from a saturated water vapour absorption band at 1.9 µm is used and clouds are detected by using a threshold technique. The basic idea behind this method is that in the clear-sky case, the amount of radiation measured by GOSAT is very small as essentially all photons are absorbed by tropospheric water vapour. When a cirrus cloud is located above most of the atmospheric water vapour, a significant amount of radiation can be backscattered and measured. A cloud is detected if the measured intensity is larger than a threshold. We use 4 times the measurement noise as threshold which has been empirically determined. This filter is sensitive to high ice clouds but not that sensitive to low water clouds. Therefore, we also filter for bright scenes by using the a priori P_0 (0th order polynomial coefficient of the albedo) obtained from GOSAT reflectances (see Sect. 5.1). If the a priori P_0 is larger than a threshold, the measurement is considered to be cloud contaminated. The threshold for this filter is 0.7 and has also been empirically determined. In addition to these cloud filters, the quality filtering removes still remaining potentially cloud contaminated scenes.

The high demands on the satellite retrievals require strict quality filtering not only for clouds. In order to minimise biases and to reduce the scatter of the data, GOSAT BESD uses filter thresholds for selected parameters. The used parameters and their filter thresholds have been selected by evaluating GOSAT XCO_2 biases and are shown in Table 3. These parameters include, e.g., parameters defining the quality of the spectral fit (χ^2, RMSE), scattering parameters (CWP, APS) and parameters defining the meteorological state (difference between fitted and a priori surface pressure).

Systematic errors have been additionally reduced by using a global bias correction scheme (similar as done by Schneising et al., 2013; Wunch et al., 2011b; Guerlet et al., 2013). We use TCCON data from all stations listed in Table 4 for the evaluation of the coefficients of the bias correction and assume that we have conditions on the TCCON stations representative for global data. Four parameters show a linear or quadratic dependence on the difference between GOSAT BESD and TCCON XCO_2. These parameters are the viewing zenith angle (VZA), the airmass factor (AMF), P_0 of band 2 (ALB) and the difference to the a priori P_0 of band 2 (ALBDIFF). The XCO_2 is corrected by using

$$XCO_2^{cor} = XCO_2 + b_0 + b_1 \cdot \text{ALBDIFF} + b_2 \cdot \text{VZA} + b_3 \cdot \text{VZA}^2 + b_4 \cdot \text{AMF}$$

AMTD
8, 1787–1832, 2015
SCIAMACHY and GOSAT BESD XCO_2 retrievals
J. Heymann et al.

$$+ b_5 \cdot \mathrm{AMF}^2 + b_6 \cdot \mathrm{ALB} \quad (3)$$

The coefficients are $b_0 = 0.4490\,\mathrm{ppm}$, $b_1 = 236.8\,\mathrm{ppm}$, $b_2 = -0.1096\,\mathrm{ppm}\,^{\circ -1}$, $b_3 = 6.750 \times 10^{-3}\,\mathrm{ppm}\,^{\circ -2}$, $b_4 = 5.961\,\mathrm{ppm}$, $b_5 = -1.912\,\mathrm{ppm}$ and $b_6 = -8.212\,\mathrm{ppm}$. Here, we use the bias corrected GOSAT BESD XCO_2 data set version 01.00.02.

6 Intercomparisons between TCCON, SCIAMACHY and GOSAT XCO_2

The quality of the satellite XCO_2 data products and their consistency has been assessed using ground-based TCCON XCO_2 observations. In this section a short overview of TCCON is given, the assessment method is described and the comparison results are discussed.

6.1 TCCON observations

The Total Carbon Column Observing Network (TCCON) (Wunch et al., 2011a) consists of several ground-based measurement stations of Fourier Transform Spectrometers (FTS). The FTS instruments measure the absorption of direct sunlight by gases. This has the advantage of being less influenced by atmospheric scattering compared to satellite measurements. From the measured spectra TCCON retrieves XCO_2, i.e., the same quantity as retrieved from satellite instruments. TCCON achieves a precision and accuracy of 0.4 ppm (1σ) (Wunch et al., 2010; Messerschmidt et al., 2011). In this study, we use TCCON version GGG2012 considering all recommended corrections from http://tccon-wiki.caltech.edu. All measurements two hours before or after the satellite measurement and all satellite data within a $10^{\circ} \times 10^{\circ}$ box surrounding the TCCON stations are used. For a comprehensive validation, data from as many TCCON stations as possible need to be used. Therefore, we have used 16 TCCON stations for the validation which have an overlapping observation period with SCIAMACHY and GOSAT. The used stations are shown in Fig. 2 and listed in Table 4.

AMTD
8, 1787–1832, 2015

6.2 Method

The first part of this study is the validation of the GOSAT BESD (available for: January 2010–December 2013) and SCIAMACHY BESD XCO_2 (available for: August 2003–March 2012) datasets using TCCON XCO_2. In order to evaluate the consistency of the satellite data products, we compare the data products with TCCON data for the same time period and perform a direct comparison of the satellite data, i.e., validation results from the overlapping observation years 2010–2011 of SCIAMACHY and GOSAT are presented and compared and a direct comparison of daily means of the datasets and an additional comparison to daily TCCON data are performed.

The comparison between different CO_2 data sets from measurements of different instruments is not trivial because of the different averaging kernels and a priori information as used by the different retrieval algorithms. To ensure, that the differences between the measurements are not dominated by differences of the averaging kernels and a priori information, Rodgers (2000) recommends to adjust the measurements by using a common a priori profile and accounting for the averaging kernels. As SCIAMACHY BESD and GOSAT BESD already use the same a priori profiles obtained from the SECM model (Reuter et al., 2012b), only the TCCON measurements need to be adjusted. However, for TCCON, the CO_2 averaging kernels are typically very close to unity and the used a priori profiles only marginally differ from the SECM profiles as SECM is based on CarbonTracker CO_2 profiles (Peters et al., 2007). Reuter et al. (2011) found, that adjusting the FTS measurements results in only small modifications of about 0.1 ppm. This is small compared to the precision of SCIAMACHY and GOSAT retrievals. Therefore, the FTS measurements are not adjusted.

Four values have been obtained from the comparisons of the datasets at the TCCON sites: (i) the number of collocated data points, (ii) the mean difference between the datasets (can be interpreted as a regional bias), (iii) the standard deviation of the difference (is an estimate of the precision when compared with TCCON) and (iv) the linear correlation coefficient between the datasets.

AMTD
8, 1787–1832, 2015

6.3 Results

6.3.1 Entire time series

Figure 3 shows time series of BESD and TCCON XCO_2 at the Lamont and Darwin TCCON sites. The qualitative comparison between SCIAMACHY BESD and GOSAT BESD XCO_2 indicates good consistency between the data sets as the satellite data are in reasonable to good agreement among themselves and with TCCON. This has been further investigated by more quantitative comparisons.

In Fig. 4a all collocated GOSAT and TCCON XCO_2 data between 2010 and 2013 and Fig. 4b all collocated SCIAMACHY and TCCON XCO_2 data between 2002 and 2012 are presented. The number of collocations are higher for SCIAMACHY/TCCON compared to GOSAT/TCCON as the time series of BESD SCIAMACHY is longer and more measurements per day were performed by SCIAMACHY. The mean difference (offset) to TCCON is −0.38 ppm for GOSAT and −0.11 ppm for SCIAMACHY. The standard deviation of the difference (single measurement precision) to TCCON is similar (~ 2 ppm) for GOSAT and SCIAMACHY. The correlation coefficient between GOSAT/TCCON is high (0.84), but slightly smaller compared to SCIAMACHY/TCCON (0.90).

In more detail, the comparison results between GOSAT BESD XCO_2 and TCCON are shown in Fig. 5. The single measurement precision is between 1.36 ppm (Darwin) and 2.65 ppm (Karlsruhe), the mean difference to TCCON is in the range −0.92 ppm (JPL) to 2.07 ppm (Tsukuba) and the correlation coefficient between GOSAT BESD and TCCON is between 0.57 (JPL) and 0.89 (Park Falls).

Figure 6 shows the detailed comparison results between the SCIAMACHY BESD XCO_2 data and the TCCON measurements for the full SCIAMACHY BESD data set (ranging from mid 2002 to mid 2012). The single measurement precision is between 1.72 ppm (Darwin) and 3.03 ppm (Lauder). The mean differences to TCCON are between −1.95 ppm (Four Corners) and 2.36 ppm (Tsukuba). The correlation coefficient is typically high and is between 0.38 (Four Corners) and 0.93 (Park Falls). The low correlation coefficient at Four Corners can be explained by the dependence of the cor-

AMTD
8, 1787–1832, 2015
SCIAMACHY and GOSAT BESD XCO_2 retrievals
J. Heymann et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

relation coefficient from the length of the time series. At Four Corners SCIAMACHY and TCCON have collocations only in one year compared to eight years at Park Falls. An additional explanation for the low correlation at Four Corners can be the collocation criterion. There are two large power plants in the vicinity of the Four Corners TCCON station introducing large variability (Lindenmaier et al., 2014) which can be smeared out in the satellite data by using the $10^\circ \times 10^\circ$ collocation criterion. This can also be a reason for the large −1.95 ppm mean difference to TCCON at Four Corners.

The numerical results shown in Figs. 5 and 6 are listed in Tables 5 and 6. In order to summarise the results, we calculate the mean of the standard deviation of the differences (can be interpreted as an upper limit for the mean single measurement precision) and the standard deviation of the mean differences, which we interpret as the relative accuracy or station-to-station biases. For the sake of completeness, we also calculate the mean of the mean differences at the TCCON stations (mean offset) and the mean correlation coefficient. However, the mean offset are less relevant as the mean offset can be simply adjusted. In order to determine robust values, we have excluded TCCON stations with less than 30 measurements in one of the comparisons, i.e., Tsukuba, JPL, Saga, Izana and Lauder are not considered.

The full dataset analysis (GOSAT: January 2010–December 2013, SCIAMACHY: August 2002–March 2012) shows for the GOSAT BESD dataset a mean offset of −0.30 ppm, a mean single measurement precision of 2.09 ppm, a mean correlation coefficient of 0.79 and a relative accuracy of 0.43 ppm. These results are similar to results of other XCO_2 products from retrieval algorithms evaluated GOSAT observations, e.g., Dils et al. (2014) found for the full-physics algorithm of the University of Leicester (Cogan et al., 2012) a mean offset of −0.76 ppm, a mean single measurement precision of 2.37 ppm, a mean correlation coefficient of 0.79 and a relative accuracy of 0.53 ppm and for SRON's RemoTeC algorithm (Butz et al., 2011) a mean offset of −0.57 ppm, a mean single measurement precision of 2.50 ppm, a mean correlation coefficient of 0.81 and a relative accuracy of 0.75 ppm. They used GOSAT data between April 2009

AMTD
8, 1787–1832, 2015

and April 2011, a collocation time of ±2 h and all measurements within a 500 km radius around a TCCON site.

The SCIAMACHY BESD data has a mean offset of −0.05 ppm, a mean single measurement precision of 2.20 ppm, a mean correlation coefficient of 0.78 and a relative accuracy of 0.89 ppm. The mean offset, the mean single measurement precision and the mean correlation coefficient are similar to the findings of Dils et al. (2014). They found a mean offset of 0.02 ppm, a slightly larger single measurement precision of 2.53 ppm and a mean correlation of 0.81. The found relative accuracy by Dils et al. (2014) is slightly better with 0.69 ppm. A reason for this difference is the large mean difference to TCCON at Four Corners (−1.95 ppm). Without Four Corners the mean offset (0.14 ppm), the mean correlation coefficient (0.82) and the mean single measurement precision (2.18 ppm) remains nearly the same, but the relative accuracy (0.67 ppm) become better and similar to the findings of Dils et al. (2014).

6.3.2 Overlapping time series (2010–2011)

For the comparisons of the validation results of GOSAT BESD and SCIAMACHY BESD, we have used the time period 2010 to 2011 where both data sets overlap. Both datasets have a negative mean difference, e.g., at Bremen (−1.01 ppm for GOSAT and −1.07 ppm for SCIAMACHY), Darwin (−1.00 ppm for GOSAT and −0.87 ppm for SCIAMACHY) and Four Corners (−0.77 and −1.61 ppm) and a positive mean difference, e.g., at Tsukuba (1.16 and 2.57 ppm) and at Garmisch (0.52 and 0.98 ppm). The single measurement precision at Karlsruhe is in both datasets similarly high (2.67 and 2.55 ppm) and similarly low at Darwin (1.24 ppm for GOSAT and 1.67 ppm for SCIAMACHY).

Overall, the analysis results for the time period 2010–2011 are similar as the results obtained for the full dataset analysis. In both comparisons, the mean offset is negative (−0.42 ppm for GOSAT and −0.08 ppm for SCIAMACHY), the mean precision is similar (2.04 ppm for GOSAT and 2.12 ppm for SCIAMACHY) and the mean correlation coefficient is high (0.71 for GOSAT and 0.63 for SCIAMACHY). The relative accuracy is slightly better for GOSAT with 0.48 ppm compared to 0.88 ppm for SCIAMACHY.

Results of the comparison of daily means of GOSAT BESD, SCIAMACHY BESD and TCCON XCO_2 are shown in Fig. 7. The daily means are computed using only days with more than three measurements within the $10^\circ \times 10^\circ$ around the TCCON sites. Figure 7 shows (similar to Fig. 4) (a) all collocated daily means of GOSAT and TCCON XCO_2 data between 2010 and 2011, (b) all collocated daily means of SCIAMACHY and TCCON XCO_2 data between 2010 and 2011 and additionally (c) all collocated daily means of GOSAT and SCIAMACHY XCO_2. The mean daily difference (offset) to TCCON is −0.34 ppm for GOSAT and 0.10 ppm for SCIAMACHY. The offset between the GOSAT and SCIAMACHY data is small with −0.60 ppm. The standard deviation of the daily difference to TCCON is for GOSAT smaller with 1.37 ppm compared to SCIAMACHY with 1.79 ppm. The standard deviation of the daily difference between GOSAT and SCIAMACHY is 1.56 ppm, which is similar to the comparison to TCCON. The correlation coefficient between GOSAT/TCCON is higher (0.86) compared to SCIAMACHY/TCCON (0.75) and similar to GOSAT/SCIAMACHY (0.82).

A more detailed comparison is shown in Fig. 8 and Table 7. Only stations with more than ten days of data are used to compute the mean values shown in Table 7. The comparison with TCCON shows for GOSAT and SCIAMACHY BESD a small negative offset of −0.17 ppm (GOSAT) and −0.05 ppm (SCIAMACHY), a daily precision of 1.28 ppm (GOSAT) and 1.60 ppm (SCIAMACHY), a mean daily correlation coefficient of 0.85 (GOSAT) and 0.73 (SCIAMACHY) and a relative daily accuracy of 0.54 ppm (GOSAT) and 0.85 ppm (SCIAMACHY). The direct comparison between the GOSAT BESD and SCIAMACHY BESD XCO_2 data set shows that the satellite data have a −0.77 ppm offset against one another. However, this can be simply adjusted by accounting for this offset. The mean scatter of the difference of 1.51 ppm and the mean correlation coefficient of 0.80 are similar to the daily precision and mean daily correlation coefficient obtained by the comparison with TCCON. The standard deviation of the mean differences between GOSAT and SCIAMACHY of 0.59 ppm is smaller/similar than the relative daily accuracy of GOSAT BESD and SCIAMACHY BESD relative to TCCON.

The differences between the satellite data are likely due to non-perfect collocations (observed air-masses are not identical) and potentially due to a non-perfect BESD retrieval algorithm. However, the similar scatter of the difference between the datasets compared to the difference to TCCON and the smaller/similar station-to-station variation of the mean difference of the datasets compared to the difference to TCCON indicate a high degree of consistency between the SCIAMACHY and GOSAT XCO_2 data sets.

7 Conclusions

As consistent long-term data sets of XCO_2 are required for carbon cycle and climate related research, we have investigated if retrievals of XCO_2 from different satellites but evaluated by using the same retrieval algorithm are consistent. For this purpose, the BESD algorithm originally developed for SCIAMACHY measurements has been modified and used to also evaluate GOSAT measurements.

The quality of the BESD data products was estimated by a validation study using TCCON observations. This comparison showed, that the GOSAT BESD XCO_2 data product has a mean offset of −0.30 ppm, a mean single measurement precision of 2.09 ppm, a mean correlation coefficient of 0.79 and a relative accuracy of 0.43 ppm. The SCIAMACHY BESD XCO_2 data product has a mean offset of −0.05 ppm, a mean single measurement precision of 2.20 ppm, a mean correlation coefficient of 0.78 and a relative accuracy of 0.89 ppm (0.67 ppm without Four Corners).

In order to evaluate the consistency of the satellite data products, we compared the data products with the TCCON data for the same time period and performed a direct comparison of the satellite data.

The comparison of the validation results for the years 2010–2011, where the observation periods of SCIAMACHY and GOSAT overlap, showed for both data sets a similar mean offset (−0.42 ppm for GOSAT, −0.08 ppm for SCIAMACHY), a similar mean single measurement precision of 2.04 ppm for GOSAT and 2.12 ppm for SCIAMACHY and a similar mean correlation coefficient for GOSAT (0.71) and SCIAMACHY (0.63). The relative accuracy for GOSAT is slightly better with 0.48 ppm compared to 0.88 ppm for SCIAMACHY.

The GOSAT BESD and SCIAMACHY BESD XCO_2 data show similarities in the comparisons at the TCCON sites. The mean difference to TCCON, e.g., is at Bremen (−1.01 ppm for GOSAT and −1.07 ppm for SCIAMACHY) and at Darwin (−1.00 ppm for GOSAT and −0.87 ppm for SCIAMACHY) similarly low and the single measurement precision has similar small values, e.g., at Darwin (1.24 ppm for GOSAT and 1.67 ppm for SCIAMACHY) and a similar high value, e.g., at Karlsruhe (2.67 ppm for GOSAT and 2.55 ppm for SCIAMACHY). These similarities and the similarity of the validation results give evidence, that the GOSAT BESD XCO_2 and the SCIAMACHY BESD XCO_2 are generally consistent.

In a direct comparison of the satellite data, we analysed daily averages of GOSAT and SCIAMACHY BESD XCO_2. This analysis showed an offset between the datasets of −0.77 ppm, a similar standard difference between the data sets (1.51 ppm) compared to the TCCON comparison (1.28 ppm for GOSAT and 1.60 ppm for SCIAMACHY), a high correlation coefficient (0.80) and smaller/similar station–to–station variations of the mean difference (0.59 ppm) compared to the difference to TCCON (0.54 ppm for GOSAT and 0.85 ppm for SCIAMACHY).

The remaining differences found between GOSAT and SCIAMACHY are likely due to non-perfect collocation (i.e., the observed air masses can be not identical), but likely also due to a non-perfect BESD retrieval algorithm. However, the similar scatter of the difference between the datasets compared to the difference to TCCON and the smaller/similar station-to-station variation of the mean difference of the datasets compared to the difference to TCCON indicate a high degree of consistency between the SCIAMACHY and GOSAT XCO_2 data set. These results confirm, that using the same

AMTD
8, 1787–1832, 2015

retrieval algorithm for the evaluation of observations from different satellite instruments can help to make satellite-based XCO_2 datasets consistent.

Our overarching goal is to generate a satellite-derived XCO_2 data set appropriate for climate and carbon cycle research covering the longest time period. We therefore also plan to extend the existing SCIAMACHY and GOSAT data set discussed here by using also data from other current or future missions, e.g., OCO-2 (Crisp et al., 2004), GOSAT-2 and CarbonSat (Bovensmann et al., 2010; Buchwitz et al., 2013a).

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Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD
8, 1787–1832, 2015

SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.

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AMTD

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SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Coefficients for empirical noise for GOSAT high (H) and medium (M) gain observations for GOSAT observations over land.

Gain mode	Emp. noise coef.	Band 1 (O_2 A) (12 920–13 195 cm^{-1})	Band 2 (weak CO_2) (6170–6278 cm^{-1})	Band 3 (strong CO_2) (4804–4896 cm^{-1})
H	a_0	1.157	1.285	1.217
	a_1	-1.843×10^{-3}	-1.639×10^{-3}	-2.301×10^{-3}
	a_2	1.506×10^{-5}	8.073×10^{-6}	2.755×10^{-5}
M	a_0	1.256	1.091	0.6401
	a_1	-2.010×10^{-3}	-7.783×10^{-3}	1.957×10^{-3}
	a_2	1.430×10^{-5}	6.615×10^{-6}	2.346×10^{-5}

AMTD
8, 1787–1832, 2015

Table 2. State vector elements of the GOSAT BESD retrieval algorithm.

State Vector Element	Quantities	A priori value	A priori uncertainty
Albedo 0th polynomial coef.	3	estimated from computed reflectance	0.1
Albedo 1st polynomial coef.	3	0.0	0.01
Albedo 2nd polynomial coef.	3	0.0	0.001
Spectral shift	3	estimated from the position of Frauenhofer lines	0.1 cm^{-1}
Shift of the solar spectrum	3	estimated from the position of Frauenhofer lines	0.1 cm^{-1}
Maximum optical path difference	3	2.5 cm	0.05 cm
Instantaneous field of view	3	15.8 mrad	0.005 mrad
Zero level offset	1	0.0 (in units $10^9\,W\,cm^{-2}\,cm\,sr^{-1}$)	1.0
CO_2 profile	10	based on SECM CO_2 model	see Reuter et al. (2010)
Surface pressure	1	based on ECMWF data	5 hPa
Temperature scaling	1	based on ECMWF data	see Reuter et al. (2010)
Water vapour profile scaling	1	based on ECMWF data	see Reuter et al. (2010)
Cloud water path	1	3 $g\,m^{-2}$	1 $g\,m^{-2}$
Cloud top height	1	10 km	2 km
Aerosol profile scaling	1	1.0	0.2

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

8, 1787–1832, 2015

SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.

Table 3. Parameters and thresholds as used for the quality filtering. A scene is considered to be of "good" quality if, e.g., the albedo difference between the fitted and a priori albedo in band 2 is larger than the lower threshold of −0.02 and smaller than the upper threshold of 0.02.

Parameter	Lower threshold	Upper threshold
Number of Iterations	–	16
Albedo Difference (weak CO_2)	−0.02	0.02
Albedo 2nd polynomial coef. (weak CO_2)	–	0.0003
Albedo slope (strong CO_2)	–	−0.003
Albedo 2nd polynomial coef. (strong CO_2)	−0.0005	–
χ^2 (O_2-A)	–	1.2
χ^2 (weak CO_2)	–	2.0
χ^2 (strong CO_2)	–	2.2
RMSE (weak CO_2)	–	0.007
Error Reduction	0.92	–
XCO_2 uncertainty	–	2.6 ppm
IFOV (O_2-A)	15.35 mrad	15.9 mrad
IFOV (weak CO_2)	15.5 mrad	–
Surface Pressure Difference	−30 hPa	20 hPa
Airmass Factor	–	3.5
Viewing Zenith Angle	–	40°

AMTD
8, 1787–1832, 2015

Table 4. Used TCCON sites, their location and used observation period.

Station	Latitude [°]	Longitude [°]	Used observation period
Sodankylä	67.37	26.63	12/02/2009–26/02/2013
Białystok	53.23	23.03	01/03/2009–30/04/2013
Bremen	53.10	8.85	24/03/2005–07/05/2013
Karlsruhe	49.10	8.44	19/04/2010–28/05/2013
Orleans	47.97	2.11	29/08/2009–07/03/2013
Garmisch	47.49	11.06	16/07/2007–28/05/2013
Park Falls	45.95	−90.27	02/06/2004–07/12/2013
Four Corners	36.80	−108.48	10/03/2011–30/05/2013
Lamont	36.60	−97.49	06/07/2008–31/12/2013
Tsukuba	36.05	140.12	25/12/2008–11/01/2013
JPL	34.20	−118.18	01/07/2007–31/03/2013
Saga	33.24	130.29	28/07/2011–26/05/2013
Izaña	28.30	−16.50	18/05/2007–23/02/2013
Darwin	−12.42	130.89	01/09/2005–30/05/2013
Wollongong	−34.41	150.88	26/06/2008–30/05/2013
Lauder	−45.04	169.68	29/06/2004–01/12/2013

AMTD
8, 1787–1832, 2015

Table 5. Results of the comparison between GOSAT BESD and TCCON XCO_2 for individual (single measurement) satellite data. Shown are the results for the full time series (January 2010–December 2013) of the data sets and for a 2010–2011 sub-set. "Δ" is the mean difference between GOSAT BESD and TCCON XCO_2, "σ" is the standard deviation of the difference, "r" is the correlation coefficient between the time series and "n" the number of collocations. Stations marked with "*" have less than 30 collocations in one of the comparisons of GOSAT BESD or SCIAMACHY BESD XCO_2 with TCCON XCO_2. Therefore, these comparisons should be interpreted with care. The mean offset (mean of the mean differences), the mean precision (mean of the standard deviation of the difference), the mean correlation coefficient and the relative accuracy (SD of the mean differences) are calculated without these stations.

Station	Full Dataset				2010–2011			
	Δ [ppm]	σ [ppm]	r [–]	n [–]	Δ [ppm]	σ [ppm]	r [–]	n [–]
Sodankylä	−0.16	1.97	0.79	37	−0.17	1.93	0.78	32
Białystok	−0.53	2.15	0.88	185	−0.75	2.26	0.78	97
Bremen	−0.88	2.31	0.76	54	−1.01	2.25	0.65	45
Karlsruhe	−0.65	2.65	0.76	271	−0.58	2.67	0.69	173
Orleans	−0.04	2.21	0.69	140	−0.12	2.24	0.66	121
Garmisch	0.60	2.50	0.78	239	0.52	2.30	0.72	159
Park Falls	0.25	1.96	0.89	402	0.19	1.79	0.79	193
Four Corners	−0.36	2.12	0.78	1145	−0.77	2.14	0.68	375
Lamont	−0.48	1.91	0.86	2199	−0.47	1.88	0.77	959
Tsukuba*	2.07	2.41	0.85	83	1.16	1.94	0.64	14
JPL*	−0.92	2.06	0.57	656	−1.95	2.02	−0.48	14
Saga*	0.03	2.26	0.88	43	−0.02	2.52	0.37	20
Izaña*	−0.33	2.09	0.64	68	−0.01	2.13	0.52	43
Darwin	−0.64	1.36	0.73	655	−1.00	1.24	0.59	163
Wollongong	−0.43	1.84	0.76	736	−0.43	1.76	0.65	340
Lauder*	0.46	1.72	0.80	139	0.33	1.84	0.33	50
MEAN	−0.30	2.09	0.79		−0.42	2.04	0.71	
SD	0.43				0.48			

AMTD
8, 1787–1832, 2015
SCIAMACHY and GOSAT BESD XCO_2 retrievals
J. Heymann et al.

Table 6. As Table 5 but for SCIAMACHY BESD XCO_2 full dataset (August 2003–March 2012).

Station	Full Dataset				2010–2011			
	Δ [ppm]	σ [ppm]	r [–]	n [–]	Δ [ppm]	σ [ppm]	r [–]	n [–]
Sodankylä	1.11	1.97	0.89	271	1.10	1.77	0.89	171
Białystok	0.23	2.29	0.77	1689	0.13	2.67	0.62	763
Bremen	−0.85	2.37	0.87	1788	−1.07	1.68	0.86	667
Karlsruhe	−0.61	2.52	0.70	1869	−0.51	2.55	0.65	1728
Orleans	0.26	2.48	0.78	1334	0.42	2.55	0.45	942
Garmisch	1.20	2.43	0.85	1987	0.98	2.51	0.59	906
Park Falls	0.30	2.07	0.93	5375	0.75	1.92	0.71	1663
Four Corners	−1.95	2.35	0.38	637	−1.61	2.10	0.37	523
Lamont	−0.19	1.89	0.85	16 520	−0.37	1.91	0.67	7204
Tsukuba*	2.36	2.35	0.74	62	2.57	2.20	0.37	23
JPL*	−0.46	2.29	0.88	1016	−0.05	2.02	0.22	64
Saga*	0.06	2.63	0.55	60	−0.32	2.38	0.16	55
Izaña*	1.75	2.12	0.81	11	2.66	2.43	0.92	6
Darwin	−0.35	1.72	0.85	11 044	−0.87	1.67	0.64	730
Wollongong	0.25	2.09	0.69	4233	0.13	2.04	0.45	2535
Lauder*	1.11	3.03	0.90	59	1.31	3.44	0.74	11
MEAN	−0.05	2.20	0.78		−0.08	2.12	0.63	
SD	0.89				0.88			

AMTD
8, 1787–1832, 2015

Table 7. Results of the comparison of daily averages of GOSAT, SCIAMACHY and TCCON XCO_2 for 2010–2011. The values are computed as for Table 6. Here, the comparisons at the TCCON sites marked with a "*", with less than 10 days of data for all three comparisons, should be interpreted with care. The mean offset (mean of the mean differences), the mean precision (mean of the standard deviation of the difference), the mean correlation coefficient and the relative accuracy (SD of the mean differences) are calculated without these stations.

Station	GOSAT – TCCON				SCIAMACHY – TCCON				GOSAT – SCIAMACHY			
	Δ [ppm]	σ [ppm]	r [–]	n [–]	Δ [ppm]	σ [ppm]	r [–]	n [–]	Δ [ppm]	σ [ppm]	r [–]	n [–]
Sodankylä*	–	–	–	2	1.26	1.24	0.94	23	–	–	–	0
Białystok	−0.33	1.58	0.85	13	0.10	1.80	0.82	39	−1.64	1.06	0.95	13
Bremen*	−0.65	1.66	0.72	11	−0.34	1.57	0.80	31	−0.74	2.05	0.76	8
Karlsruhe	−0.01	1.75	0.81	25	−0.05	1.89	0.78	81	−0.73	1.74	0.83	14
Orleans	0.51	1.70	0.87	14	0.72	1.76	0.70	40	−0.46	1.53	0.87	18
Garmisch	0.50	1.22	0.90	25	1.13	1.92	0.67	70	−1.03	1.65	0.85	15
Park Falls	0.38	0.75	0.96	19	0.93	1.30	0.88	86	−1.04	1.66	0.84	11
Four Corners	−0.70	1.56	0.78	55	−1.40	1.40	0.68	35	0.36	1.76	0.79	43
Lamont	−0.52	1.27	0.87	101	−0.37	1.75	0.72	227	−0.32	1.41	0.83	65
Tsukuba*	–	–	–	1	4.49	0.88	0.99	4	–	–	–	0
JPL*	–	–	–	3	−0.05	1.39	−0.14	4	−0.64	1.31	0.81	52
Saga*	–	–	–	1	−0.04	1.82	0.02	5	–	–	–	1
Izaña*	−0.52	1.58	0.54	9	–	–	–	0	–	–	–	0
Darwin	−0.95	0.64	0.79	22	−0.95	1.11	0.76	51	−1.30	1.12	0.64	40
Wollongong	−0.43	1.00	0.86	42	0.36	1.50	0.54	99	−0.76	1.67	0.61	35
Lauder*	0.37	1.30	0.84	5	–	–	–	1	–	–	–	0
MEAN	−0.17	1.28	0.85		−0.05	1.60	0.73		−0.77	1.51	0.80	
SD	0.54				0.85				0.59			

AMTD
8, 1787–1832, 2015

SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.

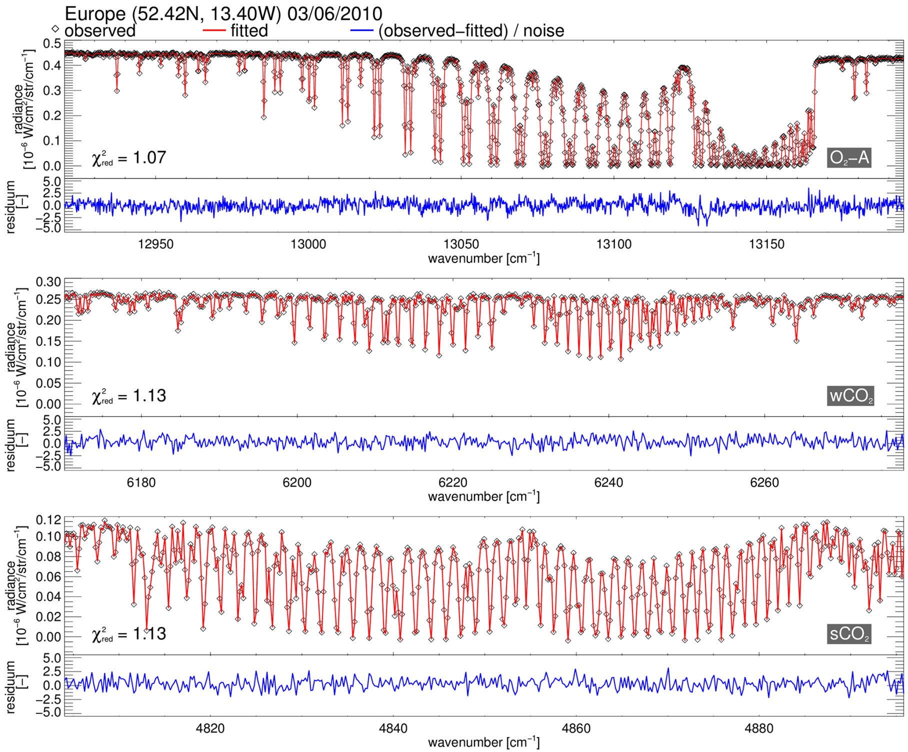

Figure 1. Observed (black) and fitted (red) intensity (radiance) and its residuum (blue) over a typical scene in Europe, Germany near Berlin (52.42° N, 13.40° E) on 3 June 2010. Top panel: observed and fitted radiance and the residuum for GOSAT band 1 (12 920–13 195 cm^{-1}). Middle panel: as top panel but for band 2 (6170–6278 cm^{-1}). Bottom panel: as top panel but for band 3 (4804–4896 cm^{-1}).

AMTD
8, 1787–1832, 2015

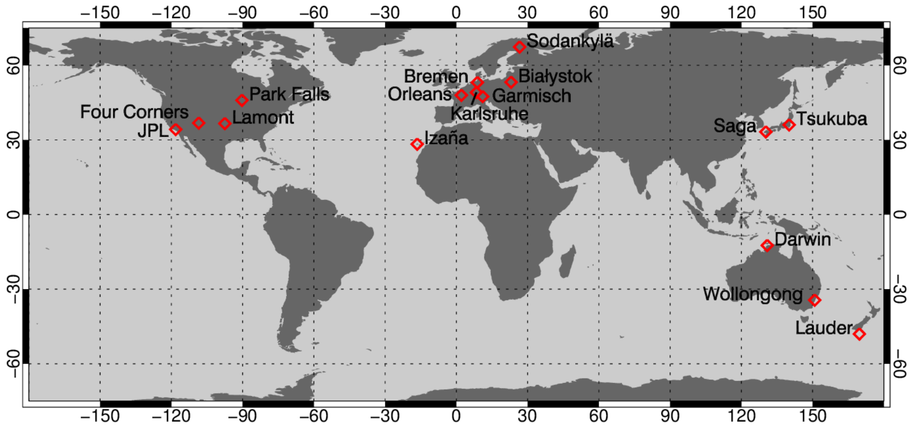

Figure 2. TCCON stations used for validation.

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8, 1787–1832, 2015

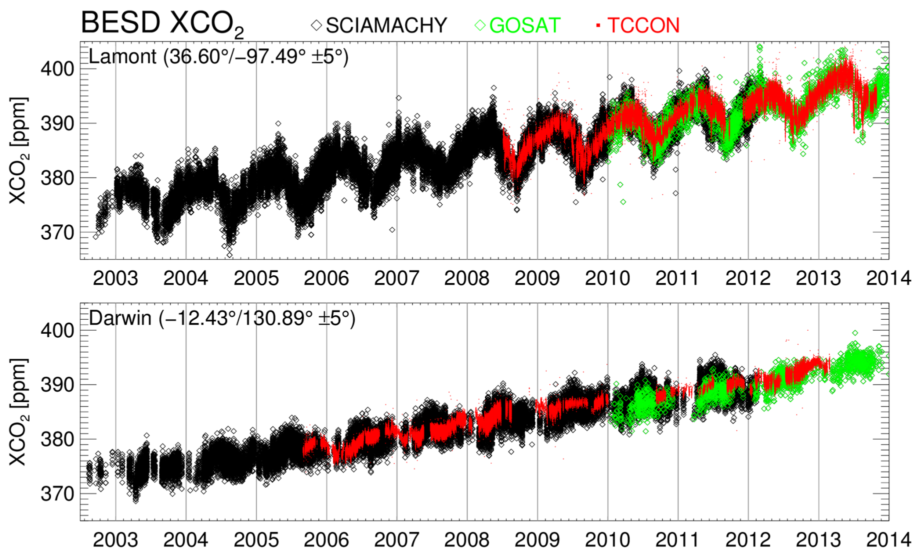

Figure 3. SCIAMACHY BESD (black), GOSAT BESD (green) and TCCON (red) XCO_2 at the Lamont (top) and Darwin (bottom) TCCON sites (±2 h, 10° × 10°).

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8, 1787–1832, 2015

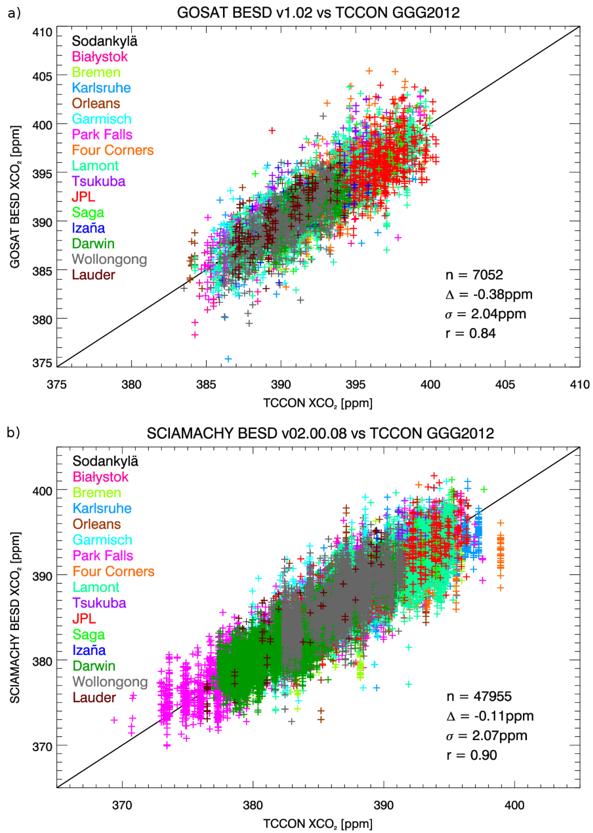

Figure 4. Scatter plots of individual satellite vs. TCCON XCO_2 measurements at the chosen TCCON sites. **(a)** GOSAT BESD XCO_2 (January 2012–December 2013) vs. TCCON XCO_2. **(b)** SCIAMACHY BESD XCO_2 (August 2002–March 2012) vs. TCCON XCO_2. "n" is the number of collocations, "Δ" is the mean difference between the satellite-based data and TCCON, "σ" is the standard deviation of the difference and "r" is the correlation coefficient.

AMTD
8, 1787–1832, 2015
SCIAMACHY and GOSAT BESD XCO_2 retrievals
J. Heymann et al.

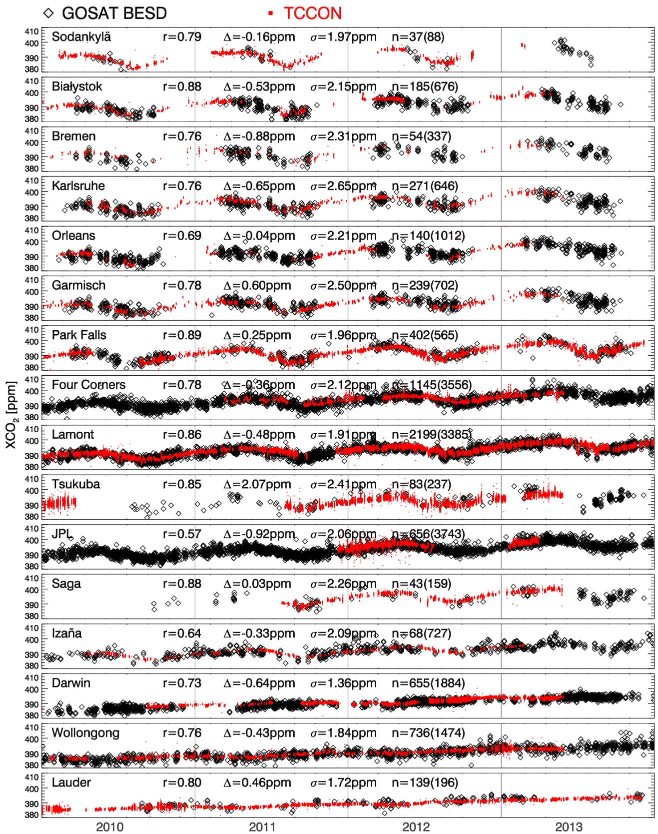

Figure 5. GOSAT BESD XCO_2 and TCCON XCO_2 at the chosen TCCON sites. "r" is the correlation coefficient, "Δ" is the mean of the difference GOSAT minus TCCON, "σ" is the standard deviation of the difference and "n" the number of collocations (±2 h, 10° × 10°, in brackets: number of GOSAT measurements with "good" quality). A summary of all values is given in Table 5.

AMTD
8, 1787–1832, 2015

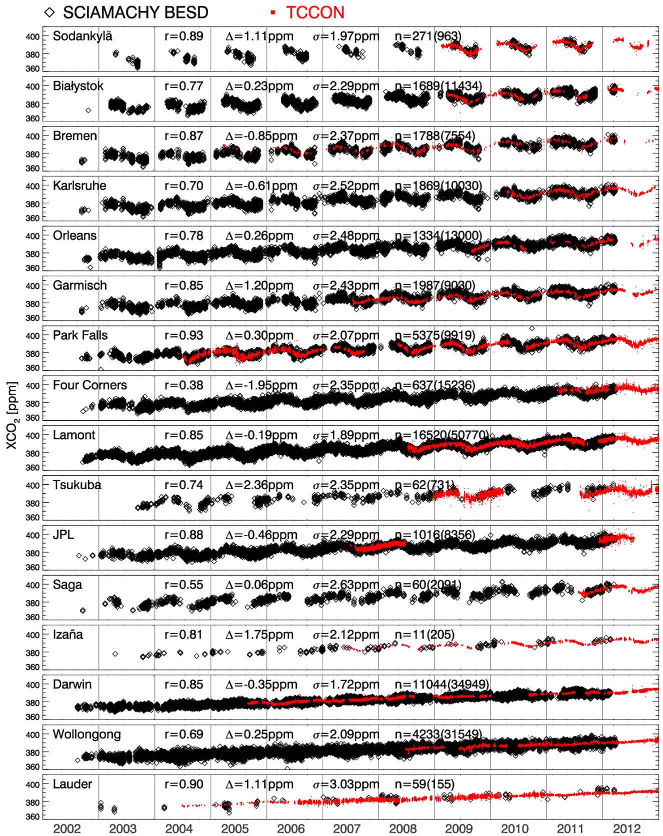

Figure 6. As Fig. 5 but for SCIAMACHY BESD XCO_2. A summary of all values is given in Table 6.

AMTD

8, 1787–1832, 2015

SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.

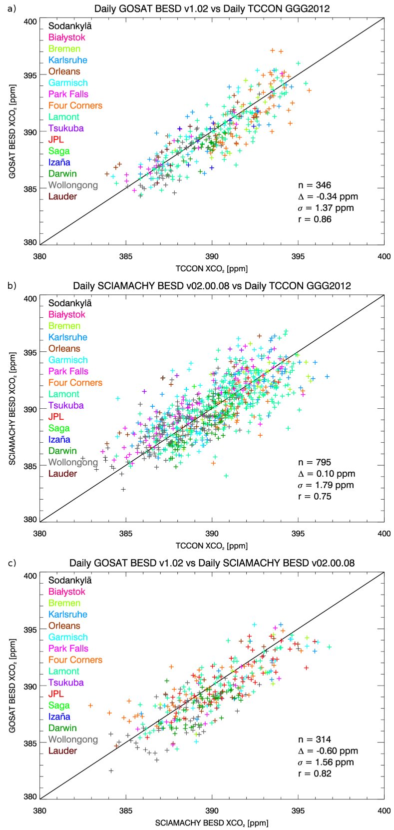

Figure 7. As Fig. 4 but for daily averages of GOSAT, SCIAMACHY and TCCON XCO_2 (2010–2011). **(a)** GOSAT BESD XCO_2 vs. TCCON XCO_2. **(b)** SCIAMACHY BESD XCO_2 vs. TCCON XCO_2. **(c)** GOSAT BESD XCO_2 vs. SCIAMACHY BESD XCO_2.

AMTD
8, 1787–1832, 2015

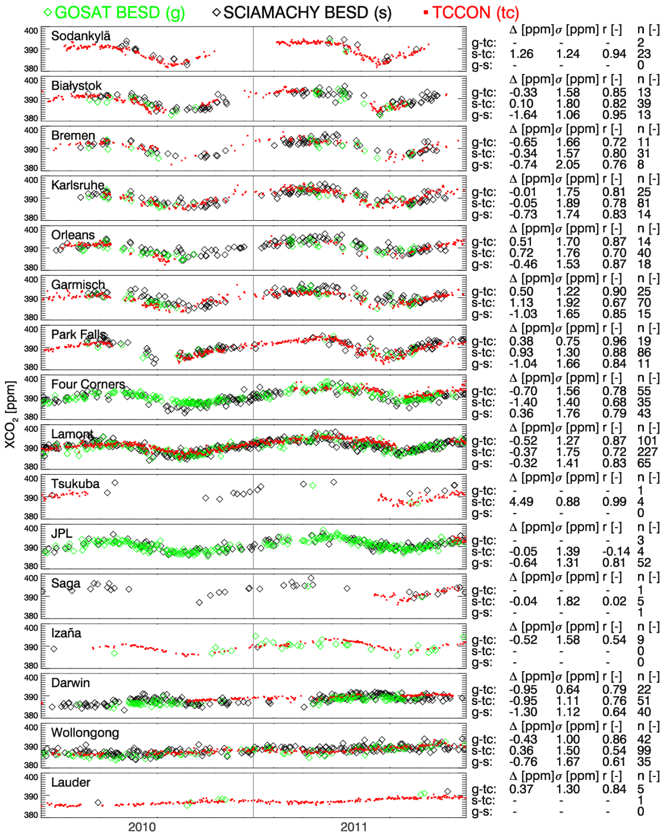

Figure 8. Daily averages of GOSAT (g), SCIAMACHY (s) and TCCON (tc) XCO_2 for 2010 and 2011. The values are computed as for Fig. 6 and are summarised in Table 7.

AMTD
8, 1787–1832, 2015

SCIAMACHY and GOSAT BESD XCO_2 retrievals

J. Heymann et al.