1   FTS measurements of column CO_2 at Sodankylä

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7   Abstract

8   Fourier Transform Spectrometer (FTS) observations at Sodankylä, Finland (67.4° N, 26.6 ° E)
9   have been performed since early 2009. The FTS instrument is participating in the Total
10   Carbon Column Observing Network (TCCON) and has been optimized to measure
11   abundances of the key greenhouse gases in the atmosphere. Sodankylä is the only TCCON
12   station in the Fennoscandia region. Here we report the measured CO_2 time series over a seven
13   year period (2009-2015) and provide a description of the FTS system and data processing at
14   Sodankylä. We find the lowest monthly column CO_2 values in August and the highest
15   monthly values during the February to May season. Inter-annual variability is the highest in
16   June-September period, which correlates with the growing season. During the time period of
17   FTS measurements from 2009 until 2015 we have observed a 2.2+/-0.2 ppm increase per year
18   in column CO_2. The monthly mean column CO_2 values have exceeded 400 ppm level for the
19   first time in February 2014.

21   1   Introduction

22   Carbon dioxide (CO_2) is the most abundant anthropogenic greenhouse gas in the atmosphere
23   (Hartman et al., 2013). The concentration of CO_2 has increased due to the burning of carbon-
24   based fuels. Precise and accurate measurements of CO_2 are needed in order to better
25   understand the carbon cycle. In addition to the relatively long term *in situ* measurements of
26   CO_2, ground based total column measurements of carbon dioxide have become possible more
27   recently. The column averaged dry-air mole fractions of carbon dioxide (XCO_2) have been
28   measured since year 2004 by the Total Carbon Column Observing Network (TCCON) sites,
29   using solar Fourier Transform Spectrometers (FTS), operating in the near infrared spectral

region (Wunch et al., 2011a). The main goal of the TCCON has been to provide precise and accurate measurements of XCO_2, but also other gases have been retrieved, including CH_4, CO, N_2O, H_2O, HDO and HF. Compared to the surface *in situ* measurements XCO_2 is less affected bychanges in the height of planetary boundary layer and the spatial sensitivity footprint is larger (Keppel-Aleks et al., 2011).. The accuracy and precision of the XCO_2 measurements within TCCON is better than 0.25% (Wunch et al., 2011a). The high accuracy and precision is needed to contribute to the carbon cycle research and validation of space borne measurements. Satellite missions that have already used the TCCON data include the Orbiting Carbon Observatory-2 (OCO-2; Crisp et al., 2004); the Greenhouse Gases Observing Satellite (GOSAT; Yokota et al., 2009) and the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY; Bovensmann et al., 1999).

Sodankylä in northern Finland is one of the stations in the TCCON. This is currently the only TCCON station in the Fennoscandia region. We established the FTS measurements at Sodankylä in early 2009. Since then the XCO_2 retrievals have been used in several studies (e.g. in Wunch et al., 2011b; Oshchepkov et al., 2012; Saito et al., 2012; Belikov et al., 2013; Guerlet et al., 2013; Yoshida et al., 2013; Agustí-Panareda, 2014; Deng et al., 2014; Reuter et al., 2014; Barthlott et al., 2015; Heymann et al., 2015; Lindqvist et al., 2015; Belikov et al., 2016; Feng et al., 2016; Inoue et al., 2016; Massart et al., 2016). This paper describes the instrumentation, measurement procedures and data processing at the Sodankylä FTS site, corresponding to the data retrieval version GGG2014 (Wunch et al., 2015). The quality controlled data from May 2009 until November 2015 have been used here to calculate the average seasonal cycle and trend of XCO_2 over the measurement period.

2   Instrumentation

The Sodankylä TCCON FTS station is part of the infrastructure of the Finnish Meteorological Institute's Arctic Research Center. The FTS is located at 67.3668° N, 26.6310 ° E, 188 m.a.s. FTS measurements at Sodankylä are made using a Bruker 125 HR FTS (Bruker Optics, Germany). Since the beginning of the data record the FTS instrument has been installed in a two-story observational building. The interior of the laboratory was rebuilt in late 2008 to mount the FTS instrument. The instrument is placed on a concrete plate, which is designed to absorb possible vibration. The solar tracker on the roof of the building is of type A547N,

manufactured by Bruker Optics. The cover of the tracker was built locally at the institute's workshop.

The FTS instrument is equipped with two room temperature detectors: an indium gallium arsenide (InGaAs, covers 4000-11000 cm^{-1}) and a silicon diode (Si, covers 9000-15000cm^{-1}), which is similar to the other FTS stations in the TCCON network. The measurements are performed in vacuum to improve stability and to reduce water vapor in the system. The system is evacuated each night to avoid vibration during the solar measurements. The optical path difference (OPD) is 45 cm and the spectral resolution is 0.02 cm^{-1}, collection time for a single scan is 78 seconds.. Column abundances of CO_2, O_2, CH_4, H_2O, HDO, HF, CO and N_2O are retrieved from the spectra.

The FTS instrument has worked in a fully automated mode since July 2013. Readings from rain and direct solar radiation sensors, combined with the automated analysis of weather radar forecast data, determine the start and cessation of daily measurements. A control system monitors the measurement quality and automatically reports on error conditions, thus longer measurement gaps have been minimized. Currently used settings are presented in Table 1. In addition to the TCCON measurements, we also take longer wavelength measurements, using a liquid nitrogen cooled indium antimonide detector (InSb, covers 1800 –6000cm^{-1}). The InSb measurements are filtered, the pass-band is at 2439-3125 cm^{-1}. This filter choice is designed for profile retrievals of methane and provides a possibility to compare the mid infrared (MIR) and near infrared (NIR) retrievals of CH_4. The sequence of measurements is such that after two InGaAs/Si scans, one InSb scan is taken. To be able to make the solar intensity variation correction, we have recorded all interferograms in the DC mode.

To guarantee the optimal performance of the instrument, the optical alignment is checked and adjusted at least once per year. Usually the alignment is performed in winter, because then the solar measurements are not possible due to the high latitude location of the station. We have applied the alignment procedure developed by Hase and Blumenstock (2001). The alignment method is based on the inspection of laser fringes through a telescope. In addition we monitor the instrument line shape (ILS) by taking HCl reference gas measurements on a monthly basis. The ILS retrievals are made using the LINEFIT14 software (Hase et al., 2013). Figure 1 presents a selection of ILS retrievals. The upper panel corresponds to the amplitude of the modulation and the lower panel to the phase error, both as functions of optical path difference. Modulation amplitude for a well-aligned FTS should be in the limits of 5% loss at

maximum optical path difference (Wunch et al., 2011a). In Sodankylä case the spread of the values of modulation amplitude is within 3 %, which is very close to the ideal value. The phase error values are measured as being close to zero (Figure 1, lower panel). A small increase in phase error was an indication of temporary scanner problems in July 2012. In general the temporal variability of the modulation efficiency is caused by the scanner wear and slight mechanical influences, which are related to small variabilities in temperature and pressure. This level of small disturbances from the ideal value of modulation efficiency is common to all well aligned spectrometers (Hase et al., 2013). Figure 1 shows that the derived modulation efficiency at maximum OPD has remained relatively stable over time, indicating that the alignment has been maintained.

3   Data processing and availability

Using the InGaAs detector, XCO_2 values are retrieved in two bands, centered at 6228 cm^{-1} and 6348 cm^{-1}. Within TCCON, the retrieval of XCO_2 and other gases is based on the GFIT algorithm as described by Wunch et al. (2011a). The data processing and analysis scheme is common at each TCCON site, although some sites may have slightly different setup of instrumentation. For example, not all the TCCON stations have the Si detector available.

XCO_2, the column-averaged dry-air mole fraction of CO_2, is defined as the ratio of CO_2 total column to the total column of all gases, excluding water. The total dry air column can be calculated either from surface pressure and water vapor column or from oxygen column, assuming the constant dry-air mole fraction of 20.95% for O_2. The oxygen column is retrieved from the TCCON FTS spectra and the method via oxygen is adopted in TCCON. XCO_2 is the ratio of CO_2 column to O_2 column,

$$XCO_2 = \frac{CO_2\ column}{O_2\ column} \times 0.2095 \tag{1}$$

By calculating the ratio, all errors that affect both columns in the same way cancel. This improves the repeatability of the XCO_2 retrieval.

The multiyear data have been reprocessed using the most recent analysis software GGG2014 (Wunch et al., 2015). From the point of view of the historical data homogenization, one of the major improvements in GGG2014 from GGG2012 is the laser sampling error (LSE) correction, which makes use of the simultaneously measured Si spectra. The LSE correction derives the laser sampling errors from Si detector measurements and resamples the

interferograms. In our data record such corrections have been necessary for measurements taken prior to March 3, 2010. Figure 2 shows the time series of the LSE derived from the Si spectra at Sodankylä. In an ideal case the LSE is small and centered around zero. Errors in the sampling of the metrology laser have been caused by faulty electronic boards in the Bruker FTS. These boards were replaced twice in case of our instrument. The ECL02 board was installed on March 10, 2010, and was replaced a year later (Table 2). The currently used electronic board (ECL05) has been operational since March 3, 2011. Intermittent fluctuations in LSE from August 27 until November 11, 2012 and again from July 6 until August 1, 2013 can be explained by scanner problems. The displacement sensor on the scanner positioning board caused fluctuations in scanner moving speed. The positioning board was replaced August 2, 2013 and since then the sampling errors have been minimal.

Another important measure of data quality and instrument performance is xAIR, the column average dry air mole fraction of dry air (Wunch et al., 2015). xAIR is the ratio of total dry air column, calculated from the surface pressure (P_S) and the measured XH_2O, to the total dry air column, obtained from the measured oxygen column:

$$xAIR = \frac{AIR\ column}{O_2\ column} \times 0.2095 - XH_2O \times \frac{m_{H_2O}}{m_{air}^{dry}} \tag{2}$$

$$AIR\ column = \frac{P_S}{\{g\}_{air} \times \frac{m_{air}^{dry}}{N_A}} \tag{3}$$

m_{H_2O} and m_{air}^{dry} are the molecular masses of water vapor and dry air, N_A is Avogadro's constant and $\{g\}_{air}$ is the column-averaged gravitational acceleration. Ideally this ratio should be 1, but typically the xAIR value is little less, around 0.98, in TCCON measurements, related to errors in the O_2 spectroscopy (Washenfelder et al., 2006). In practice xAIR is a measure of how well the instrument is capable of obtaining the oxygen column. Large differences in xAIR values compared to the network wide mean are a sign of instrument problems. The problems may be related to several factors, such as a poor optical alignment, spectral ghosts or faulty pressure sensor.

The time series of xAIR are shown in Figure 3. The average xAIR value for 2009-2011 is 0.980 and the average xAir for the time period of 2012-2015 is 0.978. The first 3 years, until 2012, correspond to the original alignment by Bruker, while the realignment since 2012 was performed using the fringe method. The method is considered an improvement over the original alignment (Hase and Blumenstock, 2001; Heikkinen et al., 2012).

The xAIR record shows that the instrument has been stable during its history. xAIR behaves consistently also during the period of relatively large sampling errors, because of the resampling included in the GGG2014 processing scheme. This was not the case with the previous version of data reprocessing system, GGG2012. In the previous data version the xAIR level was too low for the given period of measurements. During the first months of year 2009 we didn't have a dichroic beamsplitter installed and therefore we had no Si measurements. Reprocessing the earliest data, from the time period 6.2.2009-15.5.2009 needs a different approach (Dohe et al., 2013). Therefore the data from this time period have not been reprocessed using GGG2014. For the previous data version (GGG2012) we have made an additive LSE correction for the given time period, based on the data collected at different scanner speeds. Without any LSE correction the xGAS values are too low for these months by amounts ranging from 0.2 to 1.0 %. The calculated additive correction for XCO_2 is 2.5 ppm. For other gases the correction is as follows: XCO 0.86 ppb, XCH_4 0.012 ppm, XH_2O 2.9 ppm and XN_2O 2.4 ppb.

The GGG2014 data version in this study covers the time period of 15.5.2009 until 5.11.2015. During these years we have collected 111825 individual measurements, which have been spread over 966 days (Figure 4). If we add the GGG2012 data version from 6.2.2009 until 16.5.2009, then the total number of measurement is 123715 (1022 measurement days). A single measurement was graded as acceptable if the solar intensity variation during the measurement was less than 5% and the solar zenith angle was less than 82 degrees. Due to the zenith angle constraint good measurements are only possible from February 8 to November 11 each year (268 days) resulting in a gap in winter that is over 3 months long. On average there have been 146 measurement days per year. The main factor that limits the amount of measurements is cloudiness though measurement gaps also occur due to technical problems. A one month gap in the measurements was caused by the failure of sampling laser on May 20, 2012; the laser was replaced on June 20, 2012. A slight increase in the amount of measurements can be observed in 2013, because this was the first year when the instrument worked in fully automatic mode.

The reprocessed GGG2014 data version of the Sodankylä FTS measurements is available from the Carbon Dioxide Information Analysis Center (Kivi et al., 2014).

4   XCO$_2$ time series and the annual cycle

The absolute values of each of the XCO$_2$ measurements are presented in Figure 5 (upper panel), corresponding to the time period of 2009-2015. We have also included time series of other gases that are retrieved together with the XCO$_2$, using GGG2014. The other time series are for XCH$_4$, XN$_2$O, XCO, XH$_2$O and XHF measurements. The non-CO$_2$ TCCON measurements from Sodankylä have been previously published by e.g. Saito et al. (2012); Belikov et al. (2013); Yoshida et al. (2013); Saad et al. (2014); Tsuruta et al. (2015); Inoue et al. (2016).

Over the seven year time period the trend of XCO$_2$ is found to be 2.2+/-0.2 ppm/year (+/- one standard error). In Figure 6 monthly mean values are plotted for each month when measurements have been possible. The trend is in broad agreement with earlier studies (e.g. Lindqvist et al., 2015), though it is based on a longer time period. It is noteworthy that in February 2014 the monthly mean XCO$_2$ values have 400 ppm level for the first time, while individual measurements have achieved the 400 ppm level already in spring 2012 and 2013. Similar to the XCO$_2$, we find significant trend in XCH$_4$. In case of XCH$_4$ the observed increase has been 7.1 +/- 0.8 ppb/year.

The average annual cycle of XCO$_2$ is shown in Figure 7, based on 7 years of measurement. The highest values of XCO$_2$ are obtained in February to May period, before the start of the growing season. The minimum monthly XCO$_2$ occurs in August due to the uptake of carbon into the biosphere, which correlates with the period of plant growth. The interannual variability is found to be the smallest in spring (March-May) and largest in summer and autumn (June to September). The shape of the annual cycle can be explained by the imbalance between ecosystem respiration and gross primary production. This is often referred to as net ecosystem exchange (NEE). At high latitudes a negative NEE is observed during the growing season, because the gross primary production has a peak around the summer solstice, while ecosystem respiration has a maximum later in summer, in correlation with the increase in ground and air temperature (Lloyd and Taylor, 1994). Based on the TCCON measurements, Wunch et al. (2013) found that the minima in XCO$_2$ annual cycle is correlated with summertime surface temperature anomalies. The amplitude of the column CO$_2$ seasonal cycle at high latitudes of the Northern Hemisphere is smaller than the one based on surface measurement (Olsen and Randerson, 2004). Column CO$_2$ seasonal variability can be explained by the variability in the terrestrial biospheric fluxes (Keppel-Aleks et al., 2011),

while the long-term trend is driven by the fossil fuel emissions (Hartman et al., 2013). CarbonTracker (Peters et al., 2007) has been widely used to study the annual cycle of XCO_2. It has been shown that CarbonTracker is able to simulate the seasonal cycle at Sodankylä with an average model-measurement bias less than 0.4 ppm (Reuter et al., 2014). Recently the daily forecasts of CO_2 have also become available through Monitoring of Atmospheric Composition and Climate - Interim Implementation (MACC-II) service at the European Centre for Medium- Range Weather Forecasts. The model includes also the short term meteorological variability (Agustí-Panareda et al., 2014).

5   Conclusions and outlook

XCO_2 measurements have been made at Sodankylä since early 2009. The FTS instrument has been relatively stable. Regular instrument alignments and HCl cell measurements have been performed. The instrument has run in fully automatic mode since 2013, therefore the temporal data coverage is relatively good, given the high latitude conditions at Sodankylä. The historical data have been reprocessed using the GGG2014 software (Wunch et al., 2015). The data have been made available via the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA (Kivi et al., 2014). Measurements from other TCCON sites are also available from the same data center.

Based on the measurements at Sodankylä we find a 2.2+/-0.2 ppm increase per year in XCO_2 values. In February 2014 the monthly mean XCO_2 values have exceeded 400 ppm level for the first time in the history of these measurements. The lowest monthly XCO_2 values within the seasonal cycle are found in August and the highest in February-May. Year-to-year variability is lowest is March-May and highest during the growing season in June-September.

Relevant to the FTS measurements, we have started with balloon borne AirCore (Karion et al., 2010) profile measurements of CO_2, CH_4 and CO at Sodankylä in September 2013. The balloon measurements have the benefit of reaching much higher vertical altitudes (up to 30-35 km), compared to the aircraft *in situ* measurements. In addition, year around measurements by AirCore are possible. AirCore used in Sodankylä is a 100 m long coiled sampling tube, with a volume of $\approx$ 1400 ml (Paul et al., 2016). The sampling tube is filled during the payload descent and is automatically closed 9 seconds after the landing. The profile analysis has been performed typically within 2-3 hours after the landing of the payload. Gas analysis have been performed by a Cavity Ring-Down Spectrometer (Picarro Inc., CA, model G2401). Total gas

column measured by an AirCore sampling system is directly related to the World Meteorological Organization *in situ* trace gas measurement scales. Therefore the measured AirCore data can be used to contribute to the TCCON calibration (Wunch et al., 2010).

Acknowledgements

Financial support from the Academy of Finland through grant number 140408 and funding through the EU Project GAIA-CLIM is gratefully acknowledged.

1 References

2 Agustí-Panareda, A., Massart, S., Chevallier, F., Boussetta, S., Balsamo, G., Beljaars, A.,
3 Ciais, P., Deutscher, N. M., Engelen, R., Jones, L., Kivi, R., Paris, J.-D., Peuch, V.-H.,
4 Sherlock, V., Vermeulen, A. T., Wennberg, P. O., and Wunch, D.: Forecasting global
5 atmospheric CO_2, Atmos. Chem. Phys., 14, 11959-11983, doi:10.5194/acp-14-11959-2014,
6 2014.

7 Barthlott, S., Schneider, M., Hase, F., Wiegele, A., Christner, E., González, Y.,
8 Blumenstock, T., Dohe, S., García, O. E., Sepúlveda, E., Strong, K., Mendonca, J.,
9 Weaver, D., Palm, M., Deutscher, N. M., Warneke, T., Notholt, J., Lejeune, B., Mahieu, E.,
10 Jones, N., Griffith, D. W. T., Velazco, V. A., Smale, D., Robinson, J., Kivi, R., Heikkinen, P.,
11 and Raffalski, U.: Using XCO_2 retrievals for assessing the long-term consistency of
12 NDACC/FTIR data sets, Atmos. Meas. Tech., 8, 1555-1573, doi:10.5194/amt-8-1555-2015,
13 2015.

14 Belikov, D. A., Maksyutov, S., Sherlock, V., Aoki, S., Deutscher, N. M., Dohe, S.,
15 Griffith, D., Kyrö, E., Morino, I., Nakazawa, T., Notholt, J., Rettinger, M., Schneider, M.,
16 Sussmann, R., Toon, G. C., Wennberg, P. O., and Wunch, D.: Simulations of column-
17 averaged CO_2 and CH_4 using the NIES TM with a hybrid sigma-isentropic (σ-θ) vertical
18 coordinate, Atmos. Chem. Phys., 13, 1713-1732, doi:10.5194/acp-13-1713-2013, 2013.

19 Belikov, D. A., Maksyutov, S., Ganshin, A., Zhuravlev, R., Deutscher, N. M., Wunch, D.,
20 Feist, D. G., Morino, I., Parker, R. J., Strong, K., Yoshida, Y., Bril, A., Oshchepkov, S.,
21 Boesch, H., Dubey, M. K., Griffith, D., Hewson, W., Kivi, R., Mendonca, J., Notholt, J.,
22 Schneider, M., Sussmann, R., Velazco, V., and Aoki, S.: Study of the footprints of short-term
23 variation in XCO_2 observed by TCCON sites using NIES and FLEXPART atmospheric
24 transport models, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-201, 2016.

25 Bovensmann, H., Burrows, J. P., Buchwitz, M., Frerick, J., Noel, S., Rozanov, V. V., Chance,
26 K. V., and Goede. A. P. H.: SCIAMACHY - mission objectives and measurement modes, J.
27 Atmos. Sci., 56, 127-150, 1999.

28 Crisp, D., Atlas, R. M., Bréon, F.-M., Brown, L. R., Burrows, J. P., Ciais, P., Connor, B. J.,
29 Doney, S. C., Fung, I. Y., Jacob, D. J., Miller, C. E., O'Brien, D., Pawson, S., Randerson, J.
30 T., Rayner, P., Salawitch, R. S., Sander, S. P., Sen, B., Stephens, G. L., Tans, P. P., Toon, G.
31 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.

Deng, F., Jones, D. B. A., Henze, D. K., Bousserez, N., Bowman, K. W., Fisher, J. B., Nassar, R., O'Dell, C., Wunch, D., Wennberg, P. O., Kort, E. A., Wofsy, S. C., Blumenstock, T., Deutscher, N. M., Griffith, D. W. T., Hase, F., Heikkinen, P., Sherlock, V., Strong, K., Sussmann, R., and Warneke, T.: Inferring regional sources and sinks of atmospheric CO_2 from GOSAT XCO_2 data, Atmos. Chem. Phys., 14, 3703-3727, doi:10.5194/acp-14-3703-2014, 2014.

Dohe, S., V. Sherlock, F. Hase, M. Gisi, J. Robinson, E. Sepulveda, M. Schneider, and T. Blumenstock, A method to correct sampling ghosts in historic near-infrared Fourier transform spectrometer (FTS) measurements, Atmospheric Measurement Techniques, 6 (8), 1981-1992, doi:10.5194/amt-6-1981-2013, 2013.

Feng, L., Palmer, P. I., Parker, R. J., Deutscher, N. M., Feist, D. G., Kivi, R., Morino, I., and Sussmann, R.: Estimates of European uptake of CO_2 inferred from GOSAT X_{CO2} retrievals: sensitivity to measurement bias inside and outside Europe, Atmos. Chem. Phys., 16, 1289-1302, doi:10.5194/acp-16-1289-2016, 2016.

Guerlet, S., Butz, A., Schepers, D., Basu, S., Hasekamp, O. P., Kuze, A., Yokota, T., Blavier, J.-F., Deutscher, N. M., Griffith, D. W., Hase, F., Kyro, E., Morino, I., Sherlock, V., Sussmann, R., Galli, A., and Aben, I.: Impact of aerosol and thin cirrus on retrieving and validating XCO2 from GOSAT shortwave infrared measurements, J. Geophys. Res. Atmos., 118, 4887-4905, 2013.

Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., Dentener, F. J., Dlugokencky, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M., and Zhai, P. M.: Observations: Atmosphere and Surface, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159–254, 2013.

Hase, F. and Blumenstock, T.: Alignment procedure for Bruker IFS 120 spectrometers, NDSC Infrared Working Group Meeting, Bordeaux, 2001.

Hase, F., Drouin, B. J., Roehl, C. M., Toon, G. C., Wennberg, P. O., Wunch, D., Blumenstock, T., Desmet, F., Feist, D. G., Heikkinen, P., De Mazière, M., Rettinger, M., Robinson, J., Schneider, M., Sherlock, V., Sussmann, R., Té, Y., Warneke, T., and Weinzierl, C.: Calibration of sealed HCl cells used for TCCON instrumental line shape monitoring, Atmos. Meas. Tech., 6, 3527-3537, doi:10.5194/amt-6-3527-2013, 2013.

Heikkinen, P., Ahonen, P., and Kyrö, E.: High-latitude TCCON issues, IRWG/NDACC/TCCON 2012 Annual Workshop, Wengen, Switzerland, 2012.

Heymann, J., Reuter, M., Hilker, M., Buchwitz, M., Schneising, O., Bovensmann, H., Burrows, J. P., Kuze, A., Suto, H., Deutscher, N. M., Dubey, M. K., Griffith, D. W. T., Hase, F., Kawakami, S., Kivi, R., Morino, I., Petri, C., Roehl, C., Schneider, M., Sherlock, V., Sussmann, R., Velazco, V. A., Warneke, T., and Wunch, D.: Consistent satellite XCO_2 retrievals from SCIAMACHY and GOSAT using the BESD algorithm, Atmos. Meas. Tech., 8, 2961-2980, doi:10.5194/amt-8-2961-2015, 2015.

Inoue, M., Morino, I., Uchino, O., Nakatsuru, T., Yoshida, Y., Yokota, T., Wunch, D., Wennberg, P. O., Roehl, C. M., Griffith, D. W. T., Velazco, V. A., Deutscher, N. M., Warneke, T., Notholt, J., Robinson, J., Sherlock, V., Hase, F., Blumenstock, T., Rettinger, M., Sussmann, R., Kyrö, E., Kivi, R., Shiomi, K., Kawakami, S., De Mazière, M., Arnold, S. G., Feist, D. G., Barrow, E. A., Barney, J., Dubey, M., Schneider, M., Iraci, L., Podolske, J. R., Hillyard, P., Machida, T., Sawa, Y., Tsuboi, K., Matsueda, H., Sweeney, C., Tans, P. P., Andrews, A. E., Biraud, S. C., Fukuyama, Y., Pittman, J. V., Kort, E. A., and Tanaka, T.: Bias corrections of GOSAT SWIR XCO_2 and XCH_4 with TCCON data and their evaluation using aircraft measurement data, Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2015-366, 2016.

Karion, A., Sweeney, C., Tans, P., and Newberger, T.: AirCore: An Innovative Atmospheric Sampling System, J. Atmos. Ocean. Tech., 27, 1839-1853, 10.1175/2010jtecha1448.1, 2010.

Keppel-Aleks, G., Wennberg, P. O., and Schneider, T.: Sources of variations in total column carbon dioxide, Atmos. Chem. Phys., 11, 3581–3593, doi:10.5194/acp-11-3581-2011, 2011.

Kivi, R., Heikkinen, P., and Kyro, E.: TCCON data from Sodankyla, Finland, Release GGG2014R0., TCCON data archive, hosted by the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, doi:10.14291/tccon.ggg2014.sodankyla01.R0/1149280, 2014.

Lindqvist, H., O'Dell, C. W., Basu, S., Boesch, H., Chevallier, F., Deutscher, N., Feng, L., Fisher, B., Hase, F., Inoue, M., Kivi, R., Morino, I., Palmer, P. I., Parker, R., Schneider, M., Sussmann, R., and Yoshida, Y.: Does GOSAT capture the true seasonal cycle of carbon dioxide?, Atmos. Chem. Phys., 15, 13023-13040, doi:10.5194/acp-15-13023-2015, 2015.

Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration, Funct. Ecol., 8, 315, doi:10.2307/2389824, 1994.

Massart, S., Agustí-Panareda, A., Heymann, J., Buchwitz, M., Chevallier, F., Reuter, M., Hilker, M., Burrows, J. P., Deutscher, N. M., Feist, D. G., Hase, F., Sussmann, R., Desmet, F., Dubey, M. K., Griffith, D. W. T., Kivi, R., Petri, C., Schneider, M., and Velazco, V. A.: Ability of the 4-D-Var analysis of the GOSAT BESD XCO_2 retrievals to characterize atmospheric CO_2 at large and synoptic scales, Atmos. Chem. Phys., 16, 1653-1671, doi:10.5194/acp-16-1653-2016, 2016.

Messerschmidt, J., Parazoo, N., Wunch, D., Deutscher, N. M., Roehl, C., Warneke, T., and Wennberg, P. O.: Evaluation of seasonal atmosphere–biosphere exchange estimations with TCCON measurements, Atmos. Chem. Phys., 13, 5103-5115, doi:10.5194/acp-13-5103-2013, 2013.

Olsen, S. C. and Randerson, J. T.: Differences between surface and column atmospheric CO2 and implications for carbon cycle research, J. Geophys. Res., 109, D02301, doi:10.1029/2003JD003968, 2004.

Oshchepkov, S., Bril, A., Yokota, T., Morino, I., Yoshida, Y., Matsunaga, T., Belikov, D., Wunch, D., Wennberg, P. O., Toon, G. C., O'Dell, C. W., Butz, A., Guerlet, S., Cogan, A., Boesch, H., Eguchi, N., Deutscher, N. M., Griffith, D., Macatangay, R., Notholt, J., Sussmann, R., Rettinger, M., Sherlock, V., Robinson, J., Kyrö, E., Heikkinen, P., Feist, D. G., Nagahama, T., Kadygrov, N., Maksyutov, S., Uchino, O., and Watanabe, H.: Effects of atmospheric light scattering on spectroscopic observations of greenhouse gases from space: Validation of PPDF-based CO2 retrievals from GOSAT, J. Geophys. Res., 117, 1-18, 2012.

Paul, D., Chen, H., Been, H. A., Kivi, R., and Meijer, H. A. J.: Radiocarbon analysis of stratospheric CO_2 retrieved from AirCore sampling., Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2015-377, 2016.

Peters, W., Jacobson, A. R., Sweeney, C., Andrews, A. E., Conway, T. J., Masarie, K., Miller, J. B., Bruhwiler, L. M. P., Petron, G., Hirsch, A. I., Worthy, D. E. J., van der Werf, G. R.,

Randerson, J. T., Wennberg, P. O., Krol, M. C., and Tans, P. P.: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, P. Natl. Acad. Sci. USA, 104, 18925-18930, doi:10.1073/pnas.0708986104, 2007.

Reuter, M., Buchwitz, M., Hilker, M., Heymann, J., Schneising, O., Pillai, D., Bovensmann, H., Burrows, J. P., Bösch, H., Parker, R., Butz, A., Hasekamp, O., O'Dell, C. W., Yoshida, Y., Gerbig, C., Nehrkorn, T., Deutscher, N. M., Warneke, T., Notholt, J., Hase, F., Kivi, R., Sussmann, R., Machida, T., Matsueda, H., and Sawa, Y.: Satellite-inferred European carbon sink larger than expected, Atmos. Chem. Phys., 14, 13739-13753, doi:10.5194/acp-14-13739-2014, 2014.

Saad, K. M., Wunch, D., Toon, G. C., Bernath, P., Boone, C., Connor, B., Deutscher, N. M., Griffith, D. W. T., Kivi, R., Notholt, J., Roehl, C., Schneider, M., Sherlock, V., and Wennberg, P. O.: Derivation of tropospheric methane from TCCON CH_4 and HF total column observations, Atmos. Meas. Tech., 7, 2907-2918, doi:10.5194/amt-7-2907-2014, 2014.

Saito, R., Patra, P. K., Deutscher, N., Wunch, D., Ishijima, K., Sherlock, V., Blumenstock, T., Dohe, S., Griffith, D., Hase, F., Heikkinen, P., Kyrö, E., Macatangay, R., Mendonca, J., Messerschmidt, J., Morino, I., Notholt, J., Rettinger, M., Strong, K., Sussmann, R., and Warneke, T.: Technical Note: Latitude-time variations of atmospheric column-average dry air mole fractions of CO_2, CH_4 and N_2O, Atmos. Chem. Phys., 12, 7767-7777, doi:10.5194/acp-12-7767-2012, 2012.

Tsuruta, A., Aalto, T., Backman, L., Peters, W., Krol, M., Van der Laan-Luijkx, I., Hatakka, J., Heikkinen, P., Dlugokencky, E.J., Spahni, R., Paramonova, N., Evaluating atmospheric methane inversion model results for Pallas, northern Finland, Boreal Env. Res. 20: 506-525, 2015.

Washenfelder, R., Toon, G., Blavier, J., Yang, Z., Allen, N., Wennberg, P., Vay, S., Matross, D., and Daube, B.: Carbon dioxide column abundances at the Wisconsin Tall Tower site, J. Geophys. Res., 111, D22305, doi:10.1029/2006JD007154, 2006.

Wunch, D., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Stephens, B. B., Fischer, M. L., Uchino, O., Abshire, J. B., Bernath, P., Biraud, S. C., Blavier, J.-F. L., Boone, C., Bowman, K. P., Browell, E. V., Campos, T., Connor, B. J., Daube, B. C., Deutscher, N. M., Diao, M., Elkins, J. W., Gerbig, C., Gottlieb, E., Griffith, D. W. T., Hurst, D. F., Jiménez, R., Keppel-Aleks, G., Kort, E. A., Macatangay, R., Machida, T., Matsueda, H., Moore, F., Morino, I.,

Park, S., Robinson, J., Roehl, C. M., Sawa, Y., Sherlock, V., Sweeney, C., Tanaka, T., and Zondlo, M. A.: Calibration of the Total Carbon Column Observing Network using aircraft profile data, Atmos. Meas. Tech., 3, 1351-1362, doi:10.5194/amt-3-1351-2010, 2010.

Wunch D., Toon, G.C., Blavier, J.-F.L., Washenfelder, R.A., Notholt, J., Connor, B.J., Griffith, D.W.T., Sherlock, V., and Wennberg, P.O.: The Total Carbon Column Observing Network, Phil. Trans. R. Soc. A 369, 2087–2112, doi:10.1098/rsta.2010.0240, 2011a.

Wunch, D., Wennberg, P. O., Toon, G. C., Connor, B. J., Fisher, B., Osterman, G. B., Frankenberg, C., Mandrake, L., O'Dell, C., Ahonen, P., Biraud, S. C., Castano, R., Cressie, N., Crisp, D., Deutscher, N. M., Eldering, A., Fisher, M. L., Griffith, D. W. T., Gunson, M., Heikkinen, P., Keppel-Aleks, G., Kyrö, E., Lindenmaier, R., Macatangay, R., Mendonca, J., Messerschmidt, J., Miller, C. E., Morino, I., Notholt, J., Oyafuso, F. A., Rettinger, M., Robinson, J., Roehl, C. M., Salawitch, R. J., Sherlock, V., Strong, K., Sussmann, R., Tanaka, T., Thompson, D. R., Uchino, O., Warneke, T., and Wofsy, S. C.: A method for evaluating bias in global measurements of CO_2 total columns from space, Atmos. Chem. Phys., 11, 12317-12337, doi:10.5194/acp-11-12317-2011, 2011b.

Wunch, D., Wennberg, P. O., Messerschmidt, J., Parazoo, N. C., Toon, G. C., Deutscher, N. M., Keppel-Aleks, G., Roehl, C. M., Randerson, J. T., Warneke, T., and Notholt, J.: The covariation of Northern Hemisphere summertime CO2 with surface temperature in boreal regions, Atmos. Chem. Phys., 13, 9447–9459, doi:10.5194/acp-13-9447-2013, 2013.

Wunch, D., G. C. Toon, V. Sherlock, N. M. Deutscher, X. Liu, D. G. Feist, and P. O. Wennberg. The Total Carbon Column Observing Network's GGG2014 Data Version. doi:10.14291/tccon.ggg2014.documentation.R0/1221662, 2015.

Yokota, T., Yoshida, Y., Eguchi, N., Ota, Y., Tanaka, T., Watanabe, H., and Maksyutov, S.: Global concentrations of CO2 and CH4 retrieved from GOSAT: First preliminary results, SOLA, 5, 160–163, doi:10.2151/sola.2009-041, 2009.

Yoshida, Y., Kikuchi, N., Morino, I., Uchino, O., Oshchepkov, S., Bril, A., Saeki, T., Schutgens, N., Toon, G. C., Wunch, D., Roehl, C. M., Wennberg, P. O., Griffith, D. W. T., Deutscher, N. M., Warneke, T., Notholt, J., Robinson, J., Sherlock, V., Connor, B., Rettinger, M., Sussmann, R., Ahonen, P., Heikkinen, P., Kyrö, E., Mendonca, J., Strong, K., Hase, F., Dohe, S., and Yokota, T.: Improvement of the retrieval algorithm for GOSAT SWIR

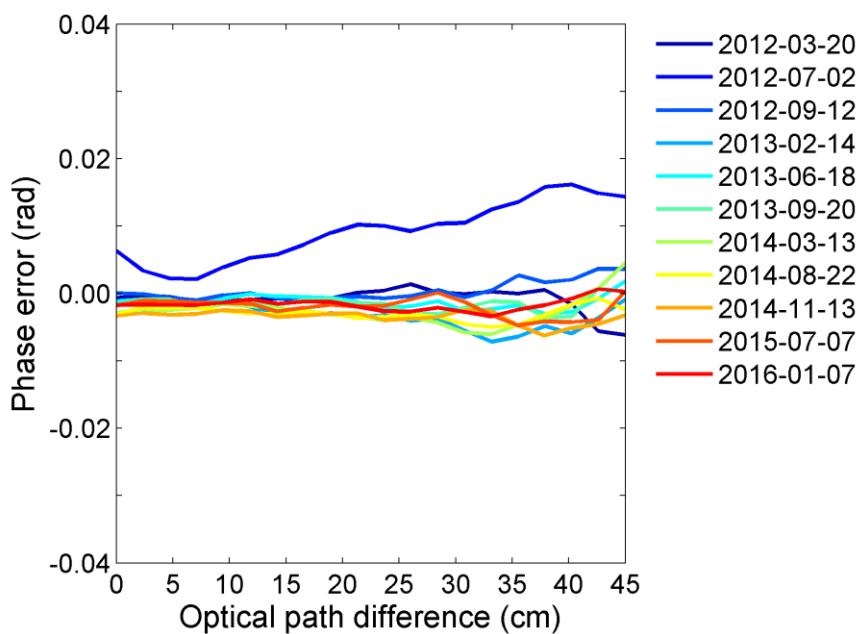
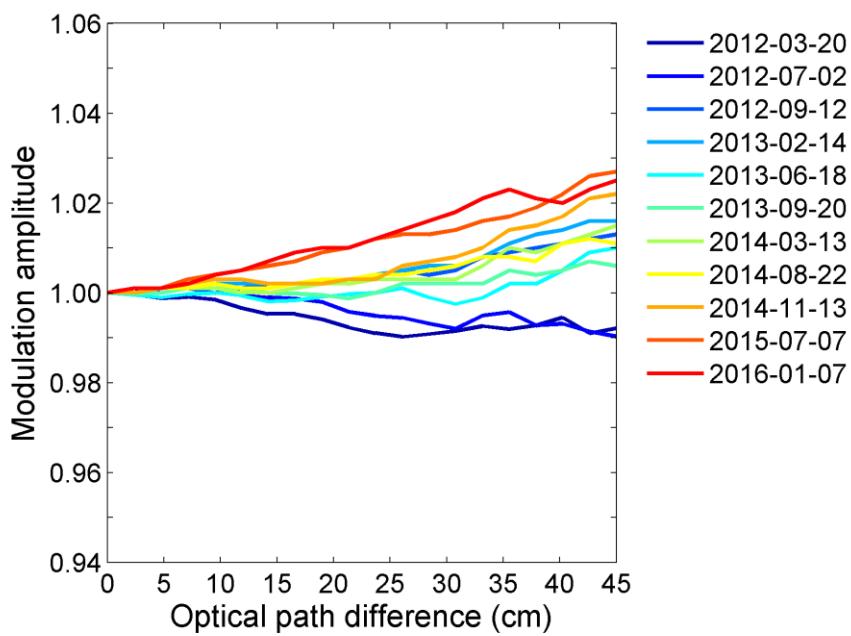
XCO$_2$ and XCH$_4$ and their validation using TCCON data, Atmos. Meas. Tech., 6, 1533-1547, doi:10.5194/amt-6-1533-2013, 2013.

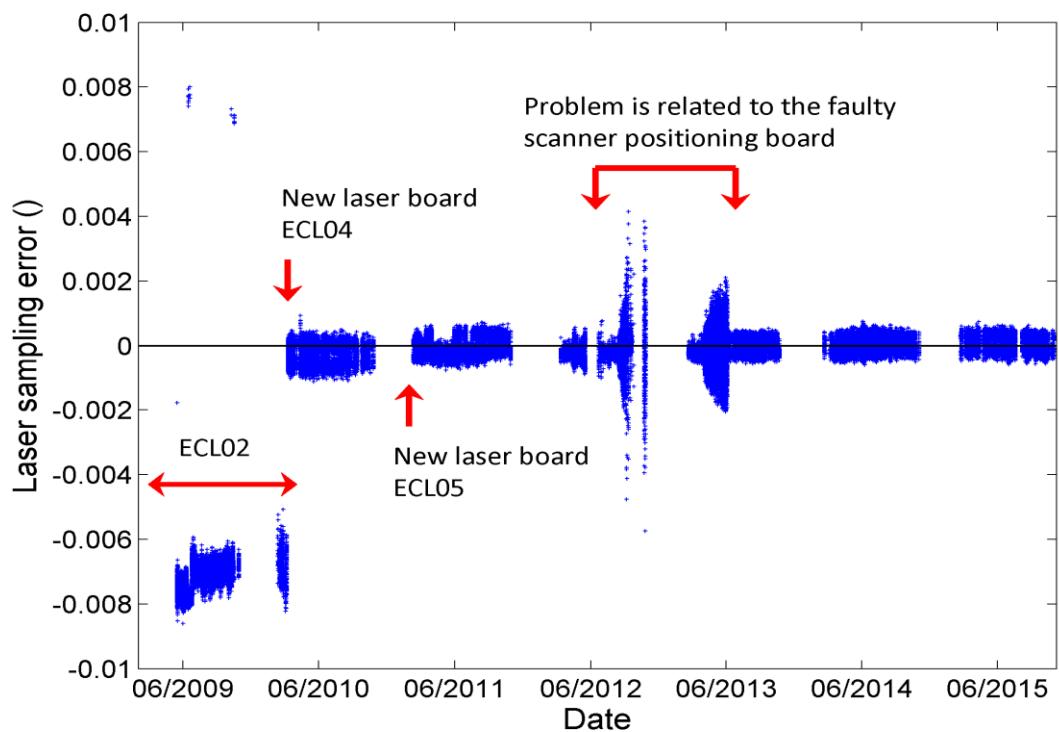
1   Table 1. Measurement settings for the Sodankylä Bruker 125HR FTS instrument.

Item	Setting
Aperture	1.0 mm
Detectors	RT-Si Diode DC + RT-InGaAs DC
Scanner velocity	10 kHz
Low Pass Filter	10 kHz
High Folding Limit	15798.007031
Resolution	0.020000
Acquisition Mode	Single Sided, Forward-Backward
Sample Scans	2

1   Table 2. Laser board settings and measurements. Ghost to parent intensity ratio GPR and the ratio of the spurious signal to primary signal

2   intensity SPR are shown at different scanner velocities. Values used for our measurements are shown in bold.

Period	Laser board	Laser detectors	Pressure hPa	Ghost minimized kHz	Filter wavenumber cm-1	Velocity kHz	GPR(4150 cm^{-1}) 10^{-4}	SPR 10^{-4}
up to 9.3.2010	ECL02	V01	0.4	-	4315	5	7.4	8.1
						10	13	8.2
						20	**26**	**7.7**
10.3.2010 to 2.3.2011	ECL04	V01	0.16	10	5960	7.5	0.42	8.0
						10	**0.75**	**8.1**
						20	8.2	8.1
						40	33	8.0
3.3.2011 to present	ECL05	V02	0.7	10	5960	7.5	0.19	8.3
						10	**0.14**	**8.4**
						20	0.56	8.4
						40	1.3	8.3

3   Figure 1. Time series of measurements of modulation efficiency: amplitude (upper panel) and

4   phase errors (lower panel) are shown as a function of optical path difference.

3 Figure 2. Laser sampling error (LSE) since 2009. LSE correction is applied during the

4 retrieval process within GGG2014.

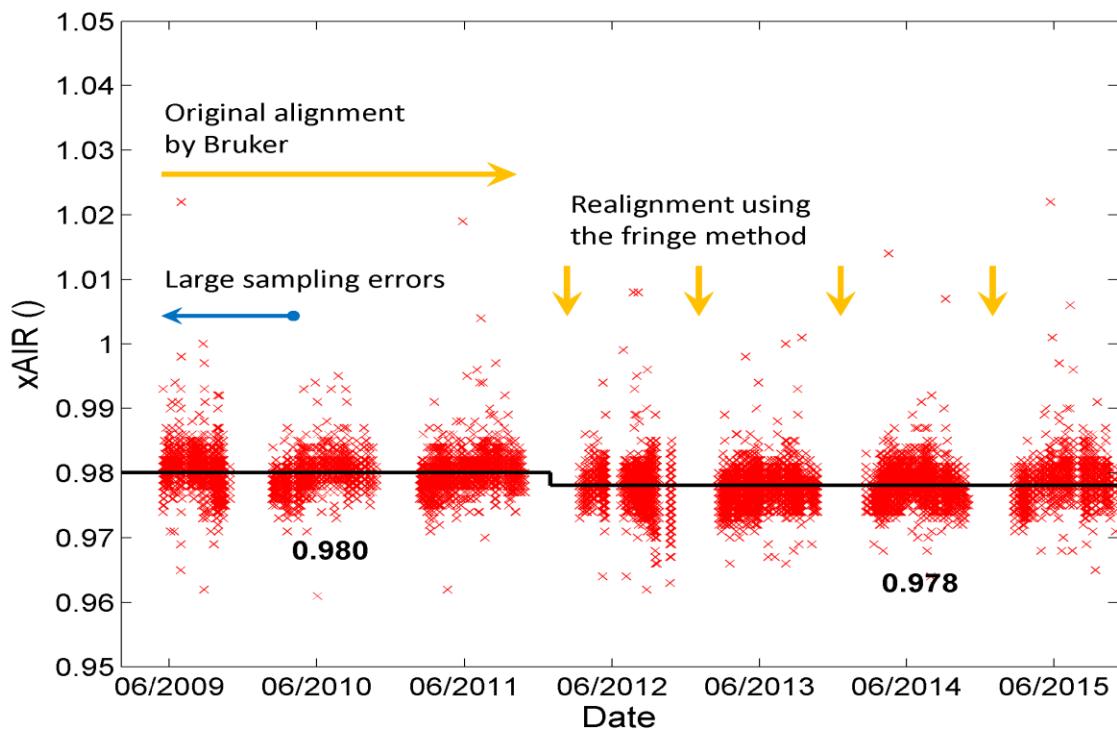
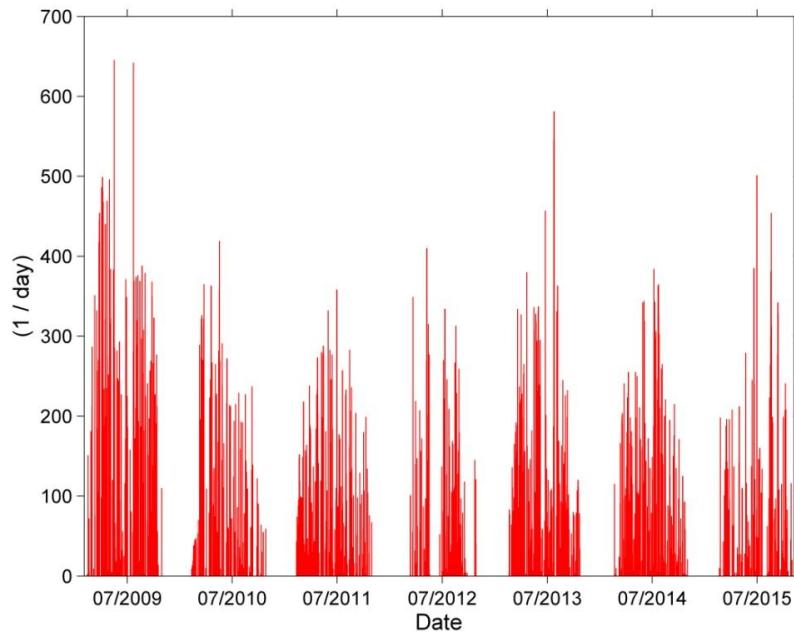
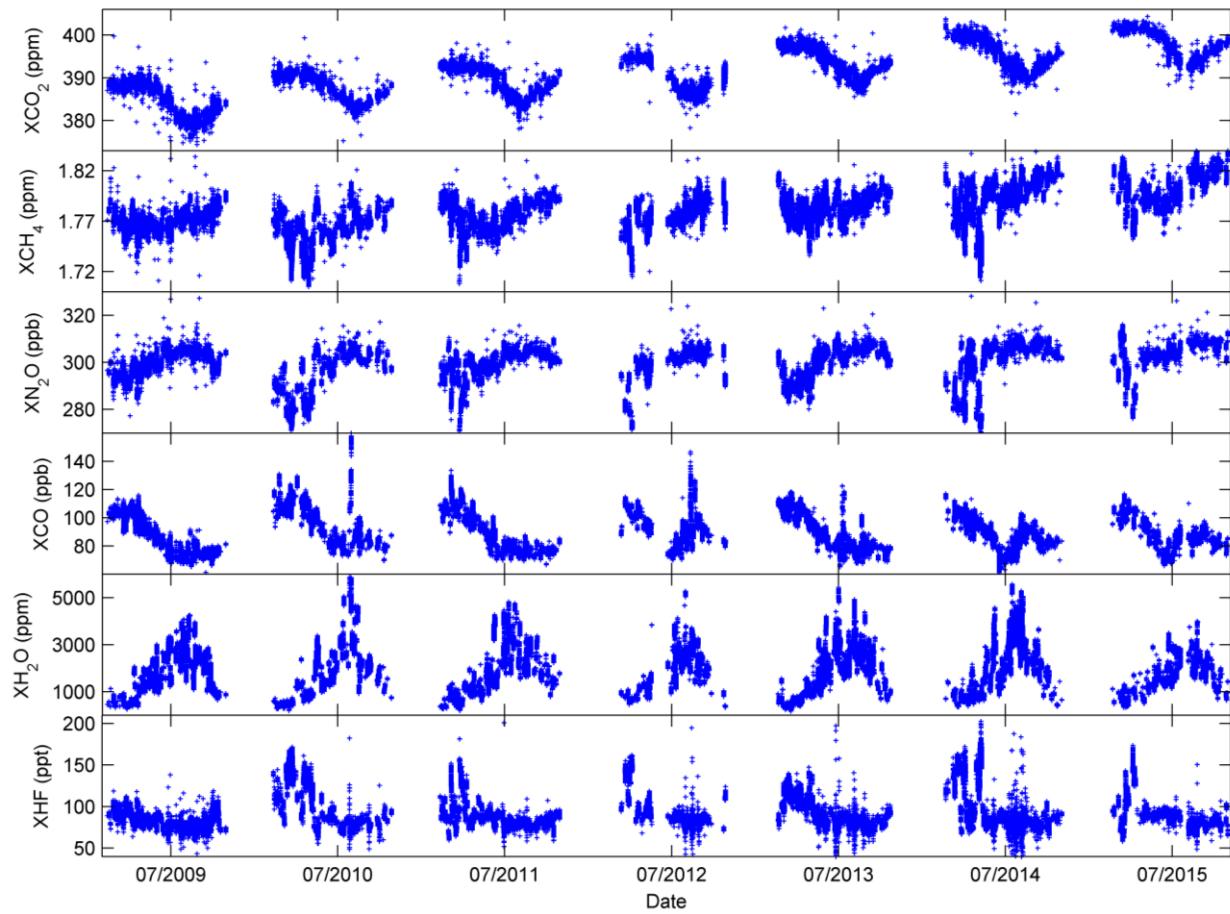



Figure 3. Time series of xAIR. Average xAIR values are shown for 2009-2011 (0.980) and for 2012-2015 (0.978).

2 Figure 4. Distribution of FTS measurements per day at Sodankylä during 2009-2015. Criteria

3 for an accepted measurement shown here is solar zenith angle < 82º and solar intensity

4 variation < 5%. In total 123715 spectra were recorded during the 7 year period, corresponding

5 to 1022 measurement days.

3   Figure 5. Time series of XCO2 measurements at Sodankylä since May 2009 (upper panel).

4   Each marker indicates a single measurement. Lower panels correspond to other gases

5   retrieved from the same measurements.

7

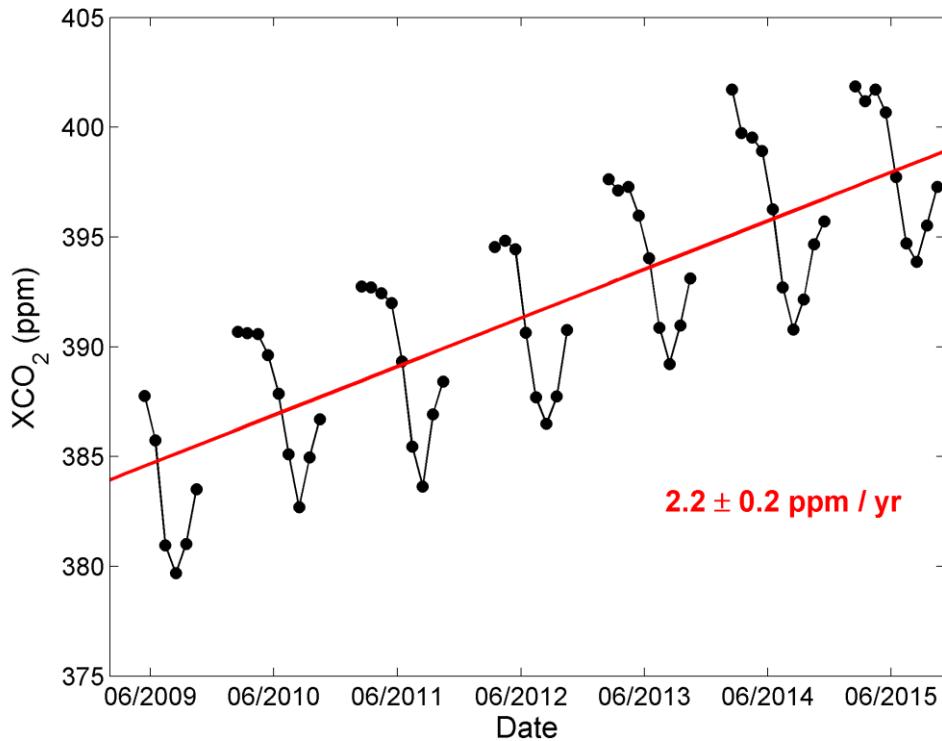
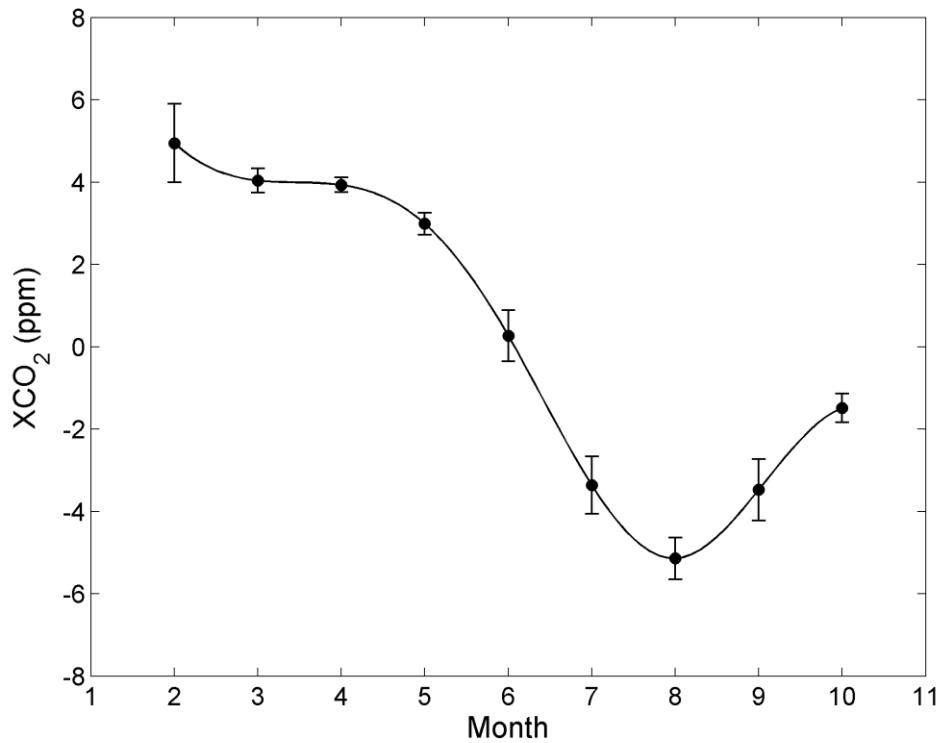



Figure 6. Time series of XCO_2 measurements at Sodankylä since May 2009. Each marker indicates monthly mean. A trend of 2.2+/-0.2 ppm per year has been observed during 2009-2015.

4 Figure 7. Average seasonal cycle of XCO_2 over Sodankylä, monthly averages (black dots)

5 and standard deviations (vertical lines). The average seasonal cycle was calculated after the

6 trend removal.