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FTS measurements of column CO_2 at Sodankylä

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Abstract

Fourier Transform Spectrometer (FTS) observations at Sodankylä have been performed since early 2009. The FTS instrument is participating in the Total Carbon Column Observing Network (TCCON) and has been optimized to measure abundances of the key greenhouse gases in the atmosphere. Here we report the measured CO_2 time series over a six year period (2009-2014) and provide a description of the FTS system and data processing at Sodankylä. We find the lowest monthly column CO_2 values in August and the highest monthly values during the February to May season. Inter-annual variability is the highest in June-September period, which correlates with the growing season. During the time period of FTS measurements from 2009 until 2014 we have observed a 2.4+/-0.3 ppm increase per year in column CO_2. The monthly mean column CO_2 values have exceeded 400 ppm level for the first time in February 2014.

1 Introduction

Carbon dioxide (CO_2) is the most abundant anthropogenic greenhouse gas in the atmosphere (Hartman et al., 2013). The concentration of CO_2 has increased rapidly due to the burning of carbon-based fuels. Precise and accurate measurements of CO_2 are needed in order to better understand the carbon cycle. In addition to the relatively long term *in situ* measurements of CO_2, also the ground based total column measurements of carbon dioxide have become possible more recently. The column averaged dry mole fractions of carbon dioxide (XCO_2) have been measured since year 2004 by the total Carbon Column Observing Network (TCCON) sites, using solar Fourier Transform Spectrometers (FTS), operating in the near infrared spectral region (Wunch et al., 2011a). Main goal of the TCCON network 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, HDF and HF. Compared to the surface in situ measurements the XCO_2 is much less affected by vertical transport. The XCO_2 values are not sensitive to variations in surface pressure and atmospheric water vapor, making results more directly comparable between different days or sites. 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. Relevant satellite missions 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 the stations in the TCCON network. 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). This paper describes the instrumentation, measurement procedures and data processing at the Sodankylä FTS site, corresponding to the data retrieval GGG2014 (Wunch et al., 2015). The quality controlled data from May 2009 until November 2014 have been used here to calculate average seasonal cycle and trend of the XCO_2 over the whole 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 67.3668º N, 26.6310 º E, 188 m.a.s. XCO_2 and other 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 has been 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 4000-12800 cm^{-1}) and a silicon diode (Si, covers 9000-15500 cm^{-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. Optical path difference is up to 45 cm, collection time for a single scan is 76 seconds, spectral resolution is 0.02 cm^{-1}. 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 is working 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. The system has been engineered having its primary purpose, the TCCON measurements, in mind. 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 1850 –10000 cm^{-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 flow 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 in a 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 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 efficiency, lower panel to the phase orientation, as a function of optical path difference. The spread of the values of modulation amplitude is within 1-2%, which is very close to the ideal value. Modulation efficiency for a well-aligned FTS should be in the limits of 5% loss at maximum optical path difference (Wunch et al., 2011). The phase orientation values are measured as being close to zero (Figure 1, lower panel). The temporal variability of the modulation efficiency is caused by the scanner wear and slight mechanical influences, which are related to a small variability 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). According to Figure 1 the instrument has stayed stable over the period of the HCl cell measurements.

3 Data processing and availability

Using the InGaAs detector, the XCO_2 values are retrieved at 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 FTS spectra and the method via oxygen is adopted in TCCON. XCO_2 is the ratio of CO_2 column to O_2 column,

$$XCO_2 = \frac{CO_2\ \text{column}}{O_2\ \text{column}} \times 0.2095 \qquad (1)$$

By calculating the ratio, all errors that affect both columns in the same way cancel. This is increasing the accuracy 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 is the laser sampling error (LSE) correction, which is making 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 concerning the measurements taken prior to March 3, 2010. Figure 2 shows time series of the LSE. In ideal case the LSE is small and centered around zero. Error in the sampling of the metrology laser has 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. The currently used electronic board (ECL05) has been operational since March 3, 2011.The intermittent fluctuations in LSE from August 27 until November 11, 2012 and again from July 6 until August 1, 2013 can be explained by the scanner problems. 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 surface pressure and water vapor column, to the total dry air column, obtained from the oxygen column. Ideally this ratio should be 1, but typically xAIR value is little less, around 0.98, in TCCON measurements, related to the errors in the O_2 spectroscopy. In practice xAIR is a measure, how well the instrument is capable to measure the oxygen column. Large differences in xAIR values compared to the network wide mean are a sign of instrument problems.

The time series of xAIR are shown in Figure 3. Average xAIR value for 2009-2011 is 0.980 and average xAir for the time period of 2012-2014 is 0.978. 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).

According to the xAIR record 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 though, based on the data collected at different scanner speeds. Without any LSE correction the xGAS values are too low for these months 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_20 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 7.11.2014. During these years we have collected 98625 individual measurements, which have been spread over 839 days (Figure 4). 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 during 8.2 – 2.11 (268 days) per year. The gap in winter is over 3 months long. On average there have been 145 measurement days per year. The main factor that limits the amount of measurements is cloudiness. Also measurement gaps are possible 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. It was the first year when the instrument worked in the fully automatic mode.

The reprocessed GGG2014 data version of the Sodankylä FTS measurements is available from the Carbon Dioxide Information Analysis Center (CDIAC) at http://tccon.ornl.gov.

4 XCO_2 time series and the annual cycle

The average annual cycle of XCO_2 is shown in Figure 5, based on the 6 years of measurement. The highest values of XCO_2 are obtained in February to May period, before the start of the growing season. 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 smallest in spring (March-May) and largest in summer and autumn (June to September). Wunch et al. (2013) found that the minima in seasonal cycle are correlated with the surface temperature anomalies in boreal regions. 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 resulting from the fossil fuel emissions (Hartman et al., 2013). Models, such as CarbonTracker (Peters et al., 2007) can be used to simulate the annual cycle of XCO_2. The CarbonTracker is able to track the seasonal cycle at Sodankylä with an average model bias less than 0.4 ppm (Reuter et al., 2014), Recently also the daily forecasts of CO_2 have become available through Monitoring of Atmospheric Composition and Climate - Interim Implementation service at the European Centre for Medium- Range Weather Forecasts. The model includes also the short term meteorological variability. Agustí-Panareda et al. (2014) found that the largest biases in the CO_2 hindcast correspond to the onset of the growing season. The measurements reveal steep decrease of XCO_2 starting from early June, while in the model the decrease in XCO_2 begins in early May.

The absolute values of each of our XCO_2 measurement are presented in Figure 6, corresponding to the time period of 2009-2014. The trend of XCO_2 is found to be 2.4+/-0.3 ppm/year. 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 exceeded 400 ppm level for the first time, while individual measurements have achieved the 400 ppm level already in spring 2012 and 2013.

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 is running in fully automatic mode since 2013, therefore the 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 2.4+/-0.3 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 the measurements. The lowest monthly XCO_2 values 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 sampling tube that is filled during the payload descent. 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).

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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

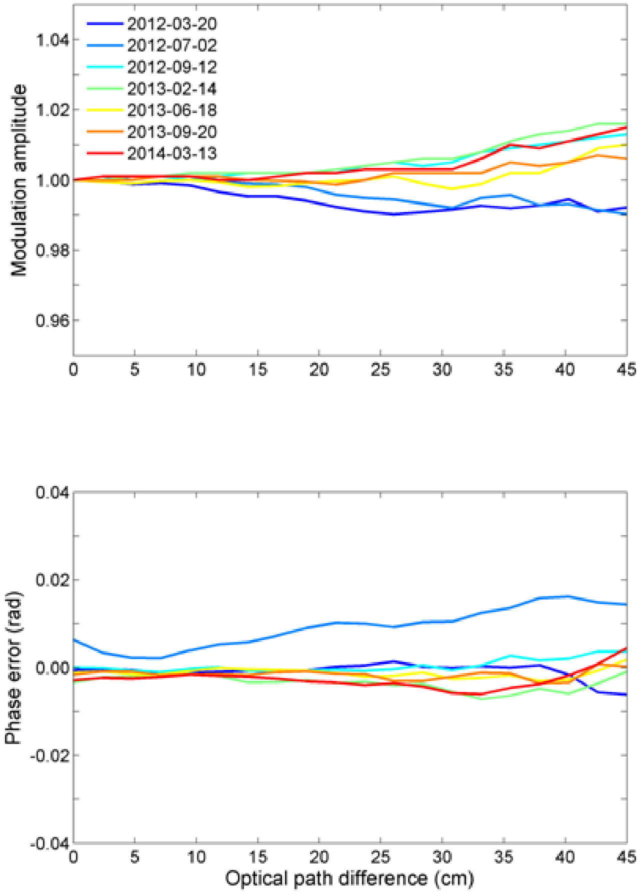

Figure 1. Time series of measurements of modulation efficiency: amplitude (upper panel) and phase orientation (lower panel) are shown as a function of optical path difference.

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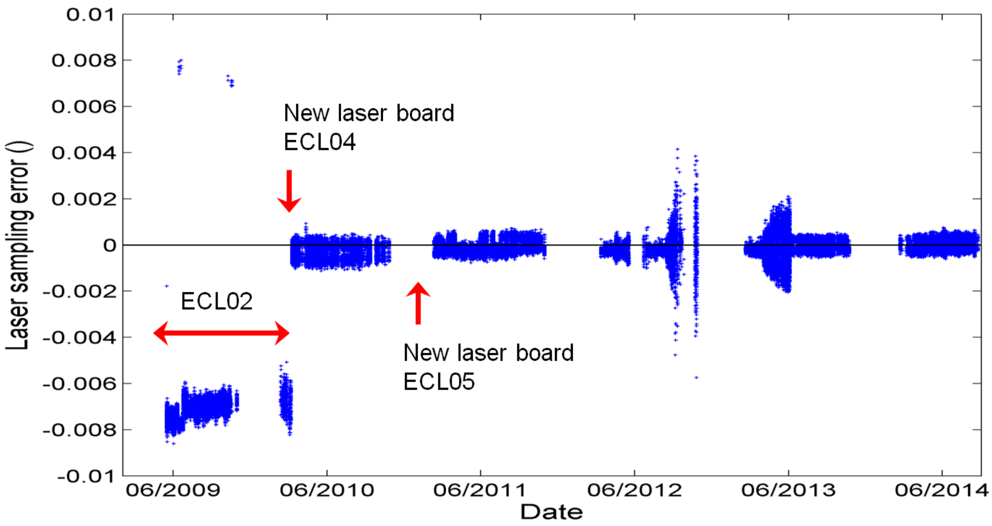

Figure 2. Laser sampling errors (LSE) measured since 2009. LSE correction is applied during the retrieval process within GGG2014.

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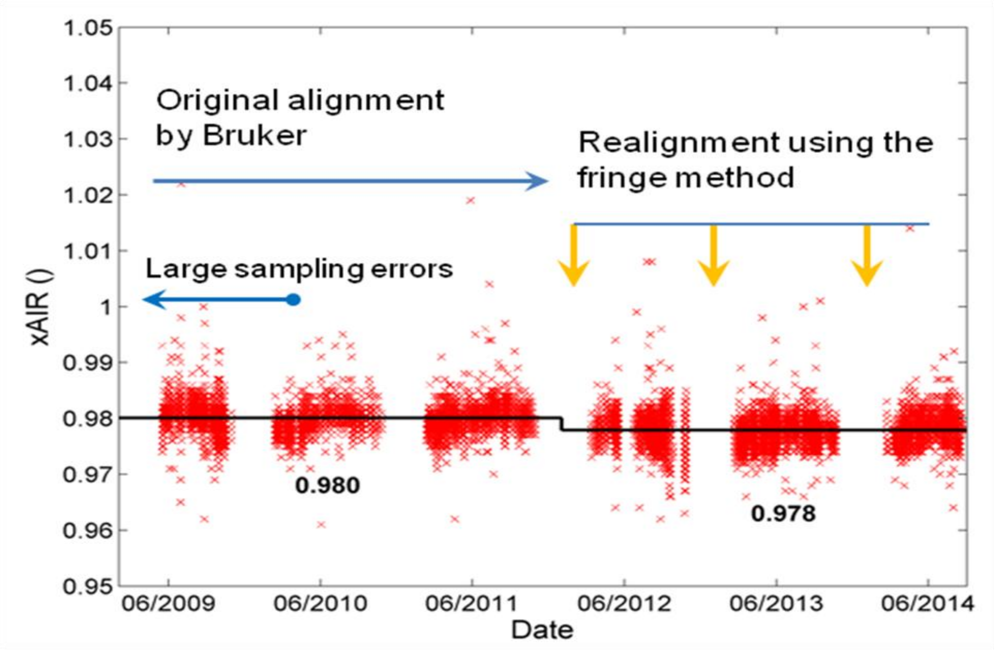

Figure 3. Time series of xAIR. Average xAIR values are shown for 2009-2011 (0.980) and for 2012-2014 (0.978).

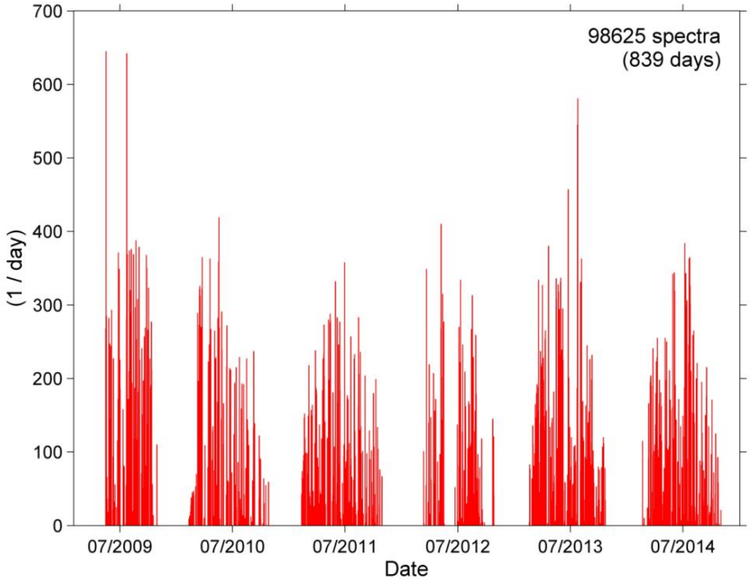

Figure 4. Distribution of FTS measurements per day at Sodankylä during 2009-20014. Criteria for an accepted measurement shown here is solar zenith angle < 82º and solar intensity variation < 5%. In total 98625 spectra were recorded during the 6 year period, corresponding to 839 measurement days, regarding the GGG2014 data version.

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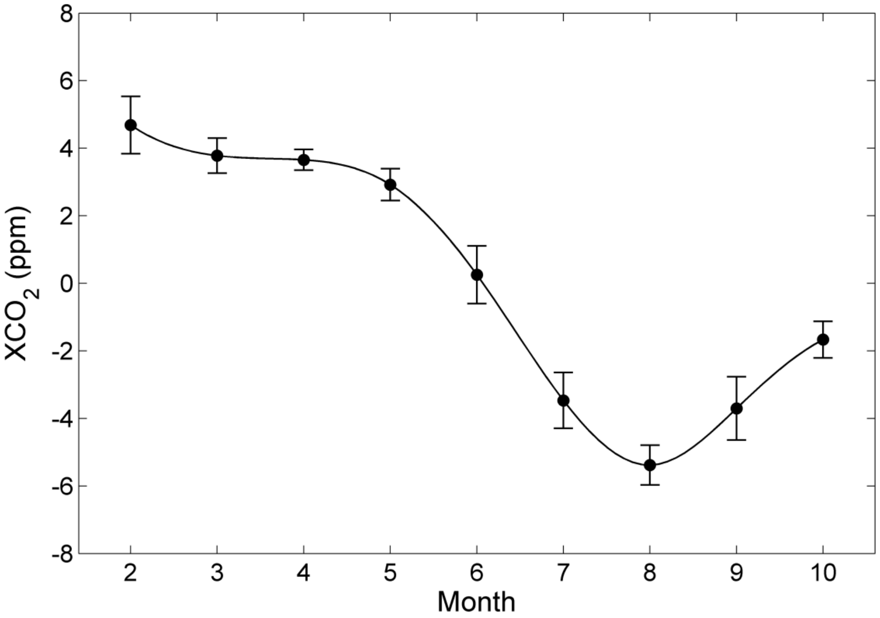

Figure 5. Average seasonal cycle of XCO_2 over Sodankylä, monthly averages (black dots) and standard deviations (vertical lines).

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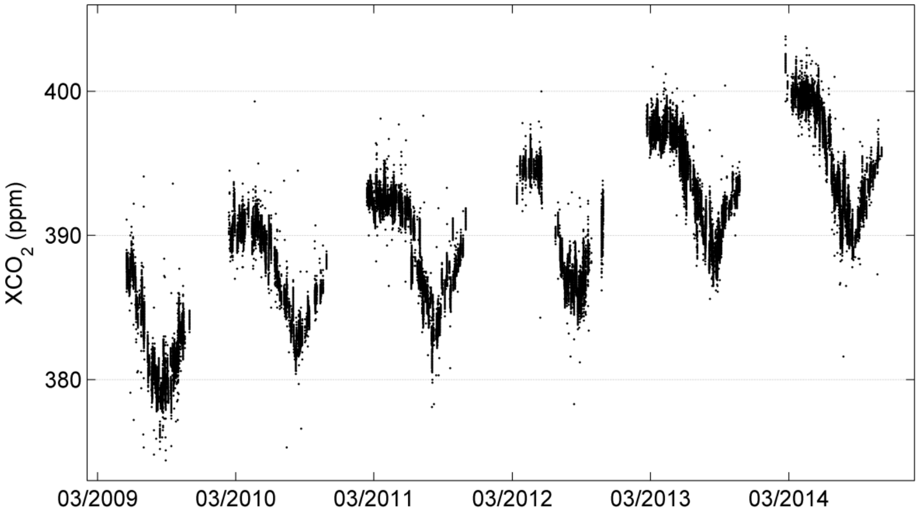

Figure 6. Time series of XCO$_2$ measurements at Sodankylä since May 2009. Each marker indicates a single measurement. A trend of 2.4+/-0.3 ppm per year has been observed during 2009-2014.