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Comparisons of Satellite (GOSAT) and Ground-Based Spectroscopic Measurements of CO_2 Content near St. Petersburg

N. M. Gavrilov and Yu. M. Timofeev

St. Petersburg State University

e-mail: gavrilov@pobox.spbu.ru

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Abstract—The column-average mole fractions of atmospheric carbon dioxide measured with ground-based Fourier-transform spectroscopy at the Peterhof station of St. Petersburg State University (59.9 N, 29.8 E) in 2009–2011 are compared with similar data obtained with the Japanese GOSAT satellite. The comparison shows that the average mole fractions of CO_2 from satellite data version V01.xx are lower by -9.8 ± 3 ppm than the corresponding values obtained from the ground-based measurements. For the GOSAT data version V02.xx, this difference is -4.7± 2.6 ppm on the average. Some overestimation of CO_2 values in measurements near St. Petersburg in comparison with the ground-based TCCON network data has been revealed indirectly, the causes of which require further explanation.

Keywords: carbon dioxide, total content, ground-based measurements, FTIR spectroscopy, GOSAT satellite, comparison, validation

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INTRODUCTION

Monitoring of atmospheric CO_2 is required for better comprehension of features of global carbon cycles and their effect on the climate change. Until recently, most CO_2 monitoring stations used the technique of airborne sampling and chemical analysis of surface or tropospheric air to determine the mole fraction of CO_2 (Convey et al., 2003). Optical spectrometry techniques can be used at monitoring stations located far from CO_2 sources and sinks for calculation of the total columnar CO_2. These techniques record IR solar radiation and measure the column-average mole fraction of CO_2 X_{CO_2}. Such a technique has been used by Russian and Kirghiz researchers at the Issyk-Kul' station since 1980. The results of the study are reviewed in (Kashin et al., 2007, 2008) in detail. In past years, high-resolution Fourier-transform spectroscopy is used for ground-based measurements of columnar CO_2 (Yang et al., 2002; Deutscher et al., 2010). Since 2009, ground-based measurements of direct solar radiation spectra in the IR range have been carried out at St. Petersburg State University (SPSU) in Peterhof (59.9 N, 29.8 E) with the use of a Bruker IFS 125 HR Fourier spectrometer of a high spectral resolution (Poberovskii et al., 2010).

Ground-based optical measurement data on CO_2 can be also useful for validation of satellite measurements, which provide for data on the total columnar CO_2. Demonstration measurements of columnar CO_2 have been carried out with the use of a SCIAMACHY instrument onboard ENVISAT since 2002 (Barkley 1
et al., 2006a, 2006b). The EOA Aqua satellite with an AIRS instrument was launched in 2004; the instrument also allows measurements of columnar CO_2. An international program of launching other instruments for global monitoring of spatiotemporal variations in the columnar CO_2 has been developed. To validate satellite monitoring data on greenhouse gases, a special ground-based Total Carbon Column Observing Network (TCCON) has been created; it uses ground-based Fourier transform infrared spectroscopy (FTIR) of direct solar radiation for routing measurements of the total content of CO_2 and other climate forcing gases (Wunch et al., 2011).

The GOSAT (Global Greenhouse Gas Observation by Satellite) satellite was launched in January 2009 for greenhouse gas monitoring. It was a joint project of the Japan Aerospace Exploration Agency and the National Institute for Environmental Studies (NIES, Tsukuba, Japan) (Kuze et al., 2009). The satellite was intended for space observation of global distributions of the total contents of CO_2 and CH_4. The column-average mole fractions of carbon dioxide X_{CO_2} and methane X_{CH_4} are retrieved from data of a TANSO-FTS sensor (Thermal And Near infrared Sensor for carbon Observations—Fourier Transform Spectrometer), which is a Fourier spectrometer focused to the study of carbon gases in the IR spectral range from onboard the GOSAT (Yoshida et al., 2011). 1
Preliminary validation of X_{CO_2} values measured from

the GOSAT was carried out in (Morino et al., 2011), as well as their comparison with TCCON FTIR data.

In this work, we compare GOSAT data on X_{CO_2} with ground-based FTIR data measured near St. Petersburg in 2009–2012.

MEASURING TECHNIQUE

Rakitin et al. (2012) presented the altitude average CO_2 mole fractions X_{CO_2} retrieved from IR spectra measured with the Bruker IFS-125HR spectrometer (Poberovskii, 2010) in the 2626.3–2627.0 cm^{-1} range at the Peterhof station of the St. Petersburg State University (about 35 km to the south-east from the center of St. Petersburg) from April 2009 to October 2011. The SFIT V3.92 software developed for NDACC (Network for the Detection of Atmospheric Composition Change) by a team of authors (Rinsland et al., 1998) was used for X_{CO_2} retrieval. The input parameters for SFIT V3.92 are solar radiation spectra, initial profiles of mole fractions of CO_2 and secondary gases, and their *a priori* variations. Relative *a priori* variations in theCO_2 mole fraction were set equal to 5% in the lower troposphere and 3% above. The software outputs assessments of the total content of CO_2 (mole/cm^2) and related random errors. To calculate the altitude average CO_2 mole fractions, daily radio sounding data of the atmosphere from Voyeykovo station were used. The HITRAN data base (2004) was used as a source of data on parameters of the fine structure of molecular absorption lines.

The contents of CH_4 and HDO wer calculated as nuisance parameters during the retrieval of the total content of CO_2. Random errors of a single measurement of the CO_2 content did not exceed 1% (~ 4 ppm) according to assessments with the calculation of the error matrix of the optimal estimation technique (implemented in the SFIT). Variations in the mole fraction of CO_2 in runs and during a day usually did not exceed 1% under conditions of stable equipment operation and stable state of the atmosphere. The X_{CO_2} values given in (Rakitin et al., 2012) were calculated as fractions of the total number of molecules (along with water vapor). The GOSAT data on X_{CO_2} relate to dry atmosphere (without contribution of water vapor); therefore, the data in (Rakitin et al., 2012) were corrected to dry atmosphere with the use of reanalysis results of meteorological data from the European Center ECMWF (Dee et al., 2011) for time points and coordinates of the site of ground-based measurements near St. Petersburg.

The satellite-measured column-average X_{CO_2} are available on the GOSAT Project website of NIES (2010). Two data versions are available: V01.xx and V02.xx; they differ in the technique for analysis of spectra measured with the TANSO-FTS. This technique for data version V01.xx is described in detail in (Yoshida et al., 2011). For simultaneous calculation of the total columnar CO_2, CH_4, and O_2, IR solar radiation absorption lines 6180–6380, 5900–6150, and 12950–13200 cm^{-1}, respectively, are used. The spectra measured are analyzed with the use of the GFIT algorithm (Toon et al., 1992; Wunch et al., 2011), which is also used at all TCCON stations (Wunch et al., 2011). Only those spectra that were measured without the influence of clouds were selected among all TANSO-FTS measured spectra. Clouds are controlled by a TANSO-CAI instrument, which operates in the visible, UV, and near-IR spectral regions.

Table 1. Time intervals and GOSAT data versions used for the comparison

@Период	Version	Number
April 8, 2009–June 25, 2009	V01.10	4
August 2, 2009–September 9, 2009	V01.20	4
April 12, 2010–September 9, 2010	V01.30	8
April 25, 2010–September 12, 2011	V01.50	7
June 6, 2009–September 21, 2009	V02.00	16
April 12, 2010–July 31, 2010	V02.00	28
July 3, 2011–July 30, 2011	V02.11	3

Random measurement errors of X_{CO_2} are assessed as 2 ppm on the average, or 0.5%, and are determined by the instrument noise (main source of errors), averaging errors, and influence of secondary gases (Yoshida et al., 2011). There are subversions inside the above versions of GOSAT data processing, e.g., V01.10, V01.20, and V01.30, which differ in the algorithms for primary processing of the Fourier spectra measured (criterions for determination of saturation and emission of spectra, see (Yoshida et al., 2011; Kuze et al., 2012)). The last GOSAT data version V02.xx (with V02.00 and V02.11 subversions) differs by its improved algorithms for primary processing and analysis of spectra, accounting for clouds and aerosol haze, and an improved model for accounting for meteorological information.

COMPARISON RESULTS

To compare X_{CO_2} measured from the ground near St. Petersburg and from GOSAT, intervals of simultaneous measurements in 2009–2011 were chosen. For these intervals, cases of GOSAT measurements of X_{CO_2} in vicinities ±3° in latitude and longitude of the site of ground-based measurements were chosen. Time intervals, versions of data analysis programs, and the number of GOSAT measurements selected for the analysis are listed in Table 1. Ground-based measurements carried out near St. Petersburg at 12–15 h of local time, when the Sun was maximally high above the horizon, were selected for the comparison. In addition, only values falling in a 95% confidence

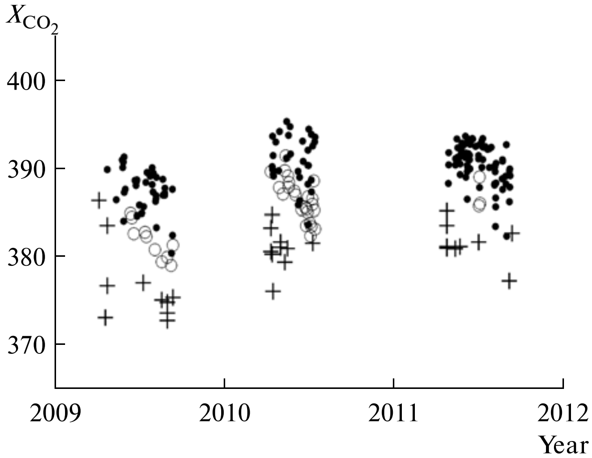

Fig. 1. Values of X_{CO_2} in ppm from ground-based measurements near St. Petersburg (dots) and from GOSAT V01.xx (crosses) and V02.xx (circles) data.

interval near the average value for a corresponding observation period were used. Ground-based measurement data on columnar CO_2 in the wet atmosphere were reduced to X_{CO_2} values in the dry air.

Figure 1 shows individual values of X_{CO_2} from ground-based and satellite measurements listed in Table 1. The dates of measurements with two methods do not coincide in many cases. However, Figure 1 shows systematically lower values of X_{CO_2} measured from GOSAT in comparison with the ground-based measured values, and the V01.xx and V02.xx data are lower than the ground-based measured values by 10 ppm and 5 ppm on the average, respectively.

Table 2. Daily average mole fractions of CO_2 for coinciding dates of ground-based measurements near St. Petersburg and GOSAT measurements (V01.xx data version)

Date	$X_{CO_2\_SPB}$, ppm	$X_{CO_2\_GOS}$, ppm	ΔX_{CO_2}, ppm
25.06.2009	389.4	380.1	−9.3
21.08.2009	388.8	375.1	−13.7
12.04.2010	393.2	382.8	−10.4
26.04.2010	390.7	381.6	−9.2
12.05.2010	392.2	380.2	−12.0
21.05.2010	394.7	387.7	−7.0
25.04.2011	389.3	384.2	−5.2
28.04.2011	398.5	386.9	−11.6
10.05.2011	392.0	387.3	−4.7
13.05.2011	394.4	381.8	−12.6
06.09.2011	388.4	378.1	−10.4
Average	392.0	382.3	−9.6
Median	392.0	381.8	−10.4
Variance	3.1	4.0	3.0

Table 2 presents mole fractions of CO_2 measured from the ground $X_{CO_2\_SPB}$ and from GOSAT $X_{CO_2\_GOS}$ (V01.xx data version), and the difference $\Delta X_{CO_2} = X_{CO_2\_GOS} - X_{CO_2\_SPB}$ for coinciding dates of ground-based and satellite measurements during the observation periods in 2009–2010 are given in Table 1. Table 3 presents data similar to Table 2 but for the V02.xx version. In the cases when several ground-based and satellite values of X_{CO_2} were recorded during a day, averaged values are used in Tables 2 and 3. Tables 2 and 3 show that ground-based measured X_{CO_2} values are higher than satellite values in most cases. Average and median values ΔX_{CO_2} in Table 3 for V02.xx data version are much lower than the corresponding values in Table 2 for V01.xx data version. This corresponds to lower positions of crosses as compared to circles in Fig. 1.

To increase the sample size, pairs of individual ground-based and satellite X_{CO_2} values for which date of measurements differed by no more than two days were analyzed. Figure 2 shows corresponding pairs of values $X_{CO_2\_SPB}$ and $X_{CO_2\_GOS}$ for both versions of GOSAT data. The solid line shows values $X_{CO_2\_SPB} = X_{CO_2\_GOS}$. It can be seen that almost all measured values lie below the solid line, i.e., $X_{CO_2\_SPB} > X_{CO_2\_GOS}$, and the difference is higher for V01.xx version than for V02.xx version. The coefficients of correlation between $X_{CO_2\_SPB}$ and $X_{CO_2\_GOS}$ in Fig. 2 are 0.65 and 0.71 for GOSAT V01.xx and V02.xx data versions, respectively. The average differences $\Delta X_{CO_2} = X_{CO_2\_GOS} -- X_{CO_2\_SPB}$ for data from Fig. 2 are given in Table 4. The short- and long-dashed lines in Fig. 2 are shifted to the average values ΔX_{CO_2} from Table 4 relative to the solid line for GOSAT data versions V01.xx and V02.xx, respectively. Figure 3 shows histograms of individual values of ΔX_{CO_2} from Fig. 2 for both versions of GOSAT data. The have maxima near (8–11) ppm and –(4–6) ppm for GOSAT data versions V01.xx and V02.xx, which correspond to the average values of ΔX_{CO_2} in Tables 2–4.

DISCUSSION

GOSAT V01.xx data were compared with X_{CO_2} measured with FTIR at nine TCCON stations in a latitude belt from 45° S to 53° N in 2009–2010 in (Morino et al., 2011), where underestimation of the satellite data by -(7–13) ppm was revealed for different stations, with the average difference $\Delta X_{CO_2} = -8.85 \pm 4.75$ ppm. A similar value of -9.08 ± 5.41 ppm was found in (Tanaka et al., 2012) for the difference between GOSAT V02.xx data on X_{CO_2} and the airborne-measured altitude average mole fraction of

Table 3. Daily average mole fractions of CO_2 for coinciding dates of ground-based measurements near St. Petersburg and GOSAT measurements (V02.xx data version)

Date	$X_{CO_2\_SPB}$, ppm	$X_{CO_2\_GOS}$, ppm	ΔX_{CO_2}, ppm
22.06.2009	389.6	383.5	–6.1
26.06.2009	387.6	384.5	–3.1
01.07.2009	386.8	382.8	–4.0
12.04.2010	393.2	390.7	–2.5
15.04.2010	390.1	391.7	1.5
26.04.2010	390.7	389.3	–1.4
12.05.2010	392.3	388.5	–3.8
14.05.2010	398.8	392.5	–6.3
19.05.2010	396.3	390.2	–6.1
20.05.2010	395.9	388.9	–7.0
21.05.2010	394.7	389.4	–5.3
17.06.2010	394.2	386.3	–7.9
28.06.2010	389.2	386.4	–2.8
05.07.2010	390.7	384.8	–5.9
12.07.2010	394.1	390.4	–3.7
13.07.2010	397.0	389.6	–7.4
26.07.2011	393.5	385.3	–8.2
Average	392.6	387.9	–4.7
Median	393.2	388.9	–5.3
Variance	3.4	3.0	2.6

CO_2. The values of ΔX_{CO_2} for the GOSAT V01.xx data version in Tables 2 and 4 mainly fall in this range, and the average and median ΔX_{CO_2} are within the limits -(9.6–10.4) ppm. This means that X_{CO_2} values measured from the ground near St. Petersburg can be higher than the TCCON mean values by 0.8–1.5 ppm on the average.

One of the reasons of the difference is the higher latitude and smaller Sun angle during observations near St. Petersburg (59.9° N) as compared with TCCON stations, which were analyzed in (Morino et al., 2011). The analysis of our measurements of X_{CO_2} on the clearest days, where several measurements were carried out, has shown systematically overestimated values in morning and evening hours as compared to the midday, when the Sun angles were maximal. Therefore, lower Sun angles can result in some overestimation of X_{CO_2} values measured in higher latitudes. Another reason for the difference is a different spectral range of measurements near St. Petersburg in comparison with TCCOM, which requires further analysis. Among the reasons for the difference, the influence of the megalopolis of St. Petersburg on ground-based measurements should also be mentioned, as it is a source of anthropogenic CO_2 (Kort et al., 2012).

The variances of individual differences ΔX_{CO_2} between GOSAT V01.xx and TCCON data are within the limits 2.8–5.6 ppm with a mean of 4.75 ppm (Morino et al., 2011). This is a little higher than the variances in Tables 2 and 4 for GOSAT V01.xx data. This might well follow from the exclusion from our analysis of X_{CO_2} values that differed from the mean values by more than doubled variance for coinciding intervals of satellite and ground-based measurements in different years.

The comparison of Tables 2–4 for different versions of GOSAT data shows that differences from the ground-based measurements are by about 5 ppm lower for the V02.xx data version than for the V01.xx version and is -4.7 ± 2.6 ppm on the average. Some works (e.g., (Notholt et al., 2012)) refer to algorithms for satellite data analysis that provide for absolute values of the differences ΔX_{CO_2} between GOSAT and TCCOM data of 1 ppm and lower. Apparently, these algorithms are under development, and their results are not widely available. In addition, the above absence of systematic differences between satellite and ground-based CO_2 measurements relates to data averaged over comparatively long periods of measurements. The analysis of data of the report (Notholt et al., 2012) shows that systematic differences between ground-based and satellite measurements of 3–6 ppm can be observed for shorter intervals (2–4 months).

Table 4. Average parameters of data in Fig. 2

Date	Estimate	$X_{CO_2\_SPB}$, ppm	$X_{CO_2\_GOS}$, ppm	ΔX_{CO_2}, ppm
V01.xx	Average	392.4	382.4	–10.0
	Median	392.9	382.8	–10.0
	Variance	3.4	3.2	2.8
V02.xx	Average	391.9	387.1	–4.8
	Median	392.0	387.1	–5.5
	Variance	3.4	3.4	2.6

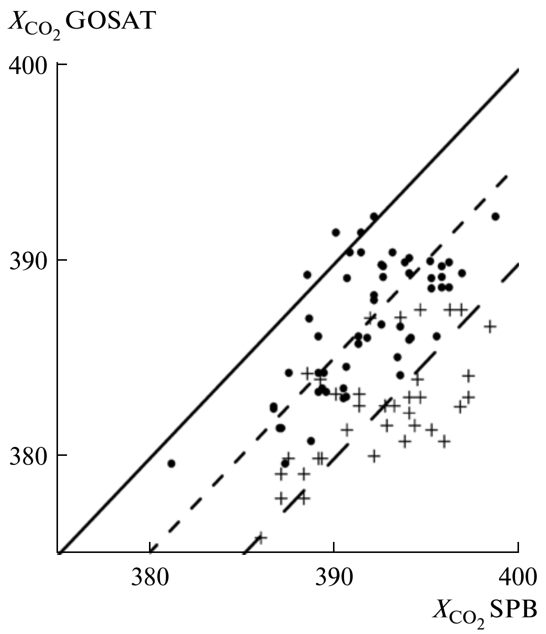

Fig. 2. Values of $X_{CO_2\_SPB}$ and $X_{CO_2\_GOS}$ in ppm measured at dates which differed by no more than 2 days. The solid line shows values $X_{CO_2\_GOS}$; vertical shifts of the short- and long-dashed lines correspond to average differences ΔX_{CO_2} for GOSAT V01.xx and V02.xx data versions, respectively.

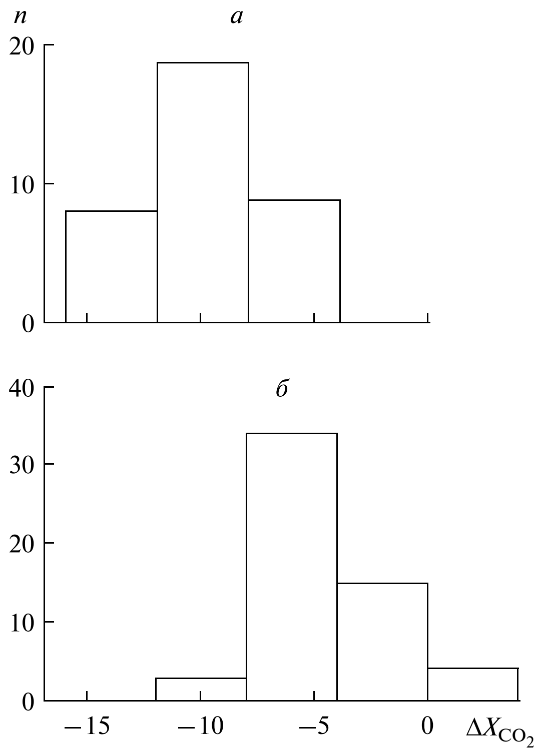

Fig. 3. Histograms of $\Delta X_{CO_2} = X_{CO_2\_GOS} - -X_{CO_2\_SPB}$ in ppm for pairs of measurements shown in Fig. 2 for GOSAT data of (a) V01.xx and (b) V02.xx versions.

Seasonal and latitude variations in GOSAT values of X_{CO_2} have been shown in (Morino et al., 2011), similar to those observed at TCCON stations. The GOSAT V02.xx data version provides for smaller differences between ground-based and satellite measurements.

CONCLUSIONS

In this work, we have compared the column-average CO_2 mole fractions X_{CO_2} measured by Fourier transform spectroscopy from the ground at Peterhof station of St. Petersburg State University (59.9 N, 29.8 E) in 2009–2011 with similar data (V01.xx and V02.xx versions) received from the Japanese GOSAT satellite. The average differences ΔX_{CO_2} between satellite data of V01.xx version and ground-based measurements are -9.8 ± 3 ppm, which agrees with literature data on the comparison between GOSAT V01.xx and TCCON data. For the GOSAT V02.xx data version, the average difference is -4.7 ± 2.6 ppm, i.e., it is two times lower than for the V01.xx version. The comparison results indirectly show some overestimation of X_{CO_2} values measured near St. Petersburg with respect to the TCCON data, the reasons of which require further investigations.

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SPELL: 1. onboard