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Comparisons of CH_4 satellite GOSAT and ground-based FTIR measurements near Saint-Petersburg (59.9° N, 29.8° E)

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Abstract

Atmospheric methane column-mean mole fractions measured with ground-based Fourier-transform spectroscopy near Saint-Petersburg, Russia (59.9° N, 29.8° E) are compared with similar data obtained with the Japanese GOSAT satellite in years 2009–2012. Average CH_4 mole fractions for the GOSAT data version V01.xx are by −13 ppb less than the corresponding values obtained from ground-based measurements on the same date (with standard deviation ∼ 26 ppb). For the GOSAT data version V02.xx the average difference is ∼ 4 ppb and standard deviation ∼ 15 ppb. This shows that FTIR spectroscopic observations near Saint-Petersburg could agree with GOSAT satellite data.

1 Introduction

Methane is the second most important anthropogenic greenhouse gas. Despite its low concentration in the Earth's atmosphere, CH_4 is responsible for about 15 % of the anthropogenic contribution to the greenhouse effect. Currently, there are networks for local flask ground and aircraft measurements within GAW (Global Atmosphere Watch) and NOAA CMDL/ESRL (Convey et al., 2003). Ground-based remote sensing optical measurements are made at the stations of international networks NDACC and TCCON. First global satellite data on the total methane content in the atmospheric column were obtained using the IMG/ADEOS equipment measuring the outgoing thermal radiation spectrum with high spectral resolution (Kobayashi et al., 1999). Further studies were carried out with satellite devices SCIAMACHY, AIRS, IASI, TES (Xiong et al., 2010; Sussmann et al., 2005; Razavi et al., 2009; Wecht et al., 2012). Despite extensive observation programs, CH_4 geographical distribution and its sources are not known sufficiently (Solomon et al., 2007). Regular global satellite methane measurements could lead to solutions of the problem.

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In January 2009, the GOSAT (Greenhouse gases Observing SATellite) was launched. It is a joint project of the Japanese Aerospace Exploration Agency and the National Institute for Environmental Studies in Tsukuba, Japan (Kuze et al., 2009). The satellite is designed to monitor global distributions of column contents of atmospheric CO_2 and CH_4 from space. Column average mole fractions of carbon dioxide, X_{CO_2}, and methane, X_{CH_4}, are retrieved from the data of TANSO-FTS (Thermal And Sensor for carbon Observation Nearinfrared Fourier Transform Spectrometer), which is a Fourier Transform Spectrometer for measurements of carbon-bearing gases in infrared range from the GOSAT satellite (Yoshida et al., 2011).

For validation of satellite observations of greenhouse gases, the special monitoring network TCCON (the Total Carbon Column Observation Network) was set up, which uses ground-based Fourier transform infra red (FTIR) spectroscopy of direct solar radiation for regular measurements of column contents of CO_2, CH_4 and other climate-forming gases (Wunch et al., 2011). Similar FTIR measurements are carried out also on the international ground-based network NDACC (Network for the Detection of Atmospheric Composition Change, http://www.ndsc.ncep.noaa.gov/). To obtain gas species contents, devices of the NDACC and TCCON networks usually use, respectively, middle and near IR spectral ranges. Sussmann et al. (2013) described an intercalibration of the measurements at both networks.

In Saint-Petersburg State University (SPbU), spectroscopic measurements of total column methane were started in 1991 (Mironenkov et al., 1996; Makarova et al., 2009). These measurements up to year 2009 were carried out using a solar IR grating spectrometer with resolution of 0.4–0.6 cm^{-1}. Since January 2009, the Atmospheric Physics Department of SPbU started ground-based solar FTIR measurements using the Bruker IFS 125 HR interferometer giving high spectral resolution. Results of atmospheric trace gas retrievals in SPbU were described by Poberovskii et al. (2010), Polyakov et al. (2011), Virolainen et al. (2011) and Yagovkina et al. (2011).

Morino et al. (2011) have performed a preliminary validation of X_{CO_2} and X_{CH_4} observed with the GOSAT satellite comparing them with measurements on the FTIR

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network TCCON (see above). They found substantially lower satellite values compared to those obtained from ground-based observations. Later, comparisons of X_{CO_2} and X_{CH_4} obtained with other retrieval algorithms for GOSAT and TCCON data gave better agreements between satellite and ground-based measurements (Notholt et al., 2012; Cogan et al., 2012; Yoshida et al., 2013). These comparisons were performed for ground-based observation sites located at latitudes lower than 55°. Therefore, it is interesting to compare GOSAT and ground-based observations performed at higher latitudes and utilizing different retrieval algorithms.

In this paper, we compare X_{CH_4} obtained by the GOSAT satellite with ground-based FTIR spectroscopic observations near Saint-Petersburg in years 2009–2012, which are performed at latitude about 60° N using modifications of retrieval algorithms designed for the international network NDACC.

2 Measurement and data processing

The FTIR measurement site of SPbU is located at the Peterhof campus (59.88° N, 29.82° E, 20 m a.s.l.), about 35 km southwest from the centre of Saint-Petersburg. The measurement tools include an automatic solar tracking system, solar flux input system, and an analog channel for cloud monitoring during the measurements. Observations are performed under a cloudless sky, or in large enough cloud cover breaks. Interferograms are usually recorded by an InSb detector for the optical path differences of 180 cm. Times of accumulation and averaging of ten scans are adjusted to obtain a single spectrum in about 12 min.

At least three popular computer programs (SFIT and PFOFIT for the NDACC and GFIT for TCCON network) exist for interpreting of ground-based FTIR observations. Comparisons of the first two algorithms and a new approach (Kozlov information operator) showed very close estimates of the methane total content using the same a priori information (see, for example, Senten et al., 2012). In the present study, we performed retrievals of total column contents of greenhouse gases in the atmosphere from the

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FTIR spectrometry using the standard software SFIT2 v 3.92 (Pougatchev et al., 1995; Rinsland et al., 1998; Hase et al., 2004) designed for the NDACC network. We used the optimal estimation technique in SFIT2 and retrievals of methane content profiles with their consequent integration.

The main input data for SFIT2 are spectra of solar radiation (including related information on interferometer parameters), and a priori profiles of atmospheric trace gases and their variations. These profiles (recommended by NDACC) were created using WACCM (Whole Atmosphere Community Climate Model) for Peterhof latitude, longitude and altitude (Garcia et al., 2007). Vertical profiles of atmospheric pressure and temperature required for retrieving of greenhouse gases are taken from the nearest site of upper air soundings Voejkovo (see, for example, Weather Web, 2013), which is located 50 km eastward from Peterhof.

Different infrared spectral intervals were used at the NDACC FTIR network for retrievals of the atmospheric column CH_4 content (Goldman et al., 1988; Schneider, 2005; Griesfeller et al., 2006; Wunch et al., 2007; Angelbratt et al., 2011; Sussmann et al., 2011, 2012; Sepulveda et al., 2012). In the present study, we use the three spectral intervals (2613.7–2615.4, 2835.5–2835.8 and 2921.0–2921.6 cm^{-1}) recommended by Sussmann et al. (2011), as well as four spectral intervals (2613.7–2615.4, 2650.6–2651.3, 2835.5–2835.8 and 2903.6–2904.03 cm^{-1}) recommended for a long time in the NDACC documentation and used by Sepulveda et al. (2012). Mean signal-to-noise ratios in these spectral bands are about 800. According to Sussmann et al. (2011), we used the HITRAN 2000 (with additions of 2001) database of spectroscopic line parameters (Rothman et al., 2003) for the above mentioned three spectral windows, and the HITRAN 2004 database (Rothman et al., 2005) for the other four windows.

Random relative errors of individual X_{CH_4} measurements do not exceed 0.3–0.5 % according to error matrix calculations within the optimal estimation method implemented in the SFIT2 software. Under stable atmospheric conditions, variations of measured X_{CH_4} within spectra series and throughout the day do not generally exceed 1 %.

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3 Results of comparison

To compare X_{CH_4} measured near Saint-Petersburg from the Earth's surface and from aboard the GOSAT satellite, we found intervals of simultaneous measurements in years 2009–2012. For these time intervals, X_{CH_4} values measured with GOSAT in ±3° latitude and longitude vicinity of the ground-based observation site were selected from the database of National Institute of Environmental Studies in Tsukuba, Japan (NIES, 2013). The ground-based X_{CH_4} values taken for the comparison were obtained at the lowest zenith angles of the Sun (usually ±3 h from local noon). We used only X_{CH_4} within the 95 % confidence interval around the mean values for the corresponding observation intervals. Because the GOSAT satellite X_{CH_4} are estimated for dry atmosphere (without water vapor), the ground-based X_{CH_4} were also adjusted to the dry atmosphere using the data of reanalysis of meteorological information by the ECMWF European Centre (Dee et al., 2011) for the moments of time and coordinates of ground-based measurements near Saint-Petersburg.

Figure 1 presents individual X_{CH_4} values from satellite and ground-based measurements using the three spectral intervals recommended by Sussmann et al. (2011). In many cases, the dates of measurements with those methods do not match exactly. However, Fig. 1 shows systematically lower X_{CH_4} for the GOSAT data version V01.xx compared to the ground-based measurements near Saint-Petersburg. Table 1 gives the daily mean $X_{CH_4\_SPB}$ and $X_{CH_4\_GOS}$ for matching dates of ground-based and GOSAT (data version V01.xx) observations, respectively. Unfortunately, the number of sunny days for FTIR spectroscopic observations and number of data pairs in Table 1 are very limited at high latitudes. In Table 1, the differences $\delta X_{CH_4} = X_{CH_4\_GOS} - X_{CH_4\_SPB}$ are negative in most cases (up to −43 ppb, or ∼ −2.4 %). The average over Table 1 $\delta X_{CH_4} = -13$ and its standard deviation ∼ 26 ppb, which shows that GOSAT CH_4 data version V01.xx are about 0.7 % lower than the ground-based FTIR values. Also, Table 1 shows slightly larger standard deviations of $X_{CH_4\_GOS}$ for the GOSAT V01.xx data than those for ground-based $X_{CH_4\_SPB}$.

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Table 2 is the same as Table 1, but for the GOSAT data version V02.xx. When several ground-based or satellite X_{CH_4} values were registered during a day, we used respective daily means in Tables 1 and 2. Deviations δX_{CH_4} between GOSAT and ground-based measurements have different signs for different days in Table 2, and vary from −21 ppm (−1.2 %) to 31 ppm (1.8 %), which is smaller than deviations for data version V01.xx in Table 1. In most cases, the relative deviations are less than 1 % in Table 2. The average difference is δX_{CH_4} = 3.7 ppb (or about 0.2 %) for the GOSAT CH_4 data version V02.xx and the ground-based FTIR measurements. Standard deviation of average δX_{CH_4} in Table 2 is 15.1 ppb, or less than 1 %. In addition, variability (standard deviation) of methane mole fractions is significantly smaller (6.5 ppb) for the GOSAT V02.xx data than for ground-based measurements (17 ppb) in Table 2.

To increase the amount of compared data, we also analyzed the individual couples of ground-based and satellite X_{CH_4} values, for which the difference in dates of their measurements do not exceed two days. Figure 2 shows the corresponding pairs of $X_{CH_4\_SPB}$ and $X_{CH_4\_GOS}$ for both versions of the GOSAT satellite data. The solid line in Fig. 2 corresponds to $X_{CH_4\_SPB} = X_{CH_4\_GOS}$. One can see that almost all of the measured X_{CH_4} values for the GOSAT V01.xx data lie below the solid line in Fig. 2, while for the GOSAT V02.xx data the situation is different.

Table 3 shows the mean, median characteristics and standard deviations calculated for the ground-based and satellite data presented in Fig. 2. The mean and median values in Table 3 for both types of measurements are closer to each other for the GOSAT V02.xx data. The long- and short-dashed lines in Fig. 2 have shifts relative to the solid line according to the average δX_{CH_4} values from Table 3 for the GOSAT data versions V01.xx and V02.xx, respectively.

Figure 3 reveals histograms of differences δX_{CH_4} between pairs of measurements presented in Fig. 2. For the GOSAT data version V02.xx the deviations are almost symmetrical respective to zero in Fig. 3b, while Fig. 3a demonstrates systematic underestimation of the X_{CH_4} from the GOSAT V01.xx data compared to the ground-based FTIR measurements.

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The results presented above were obtained using the three spectral intervals listed in Sect. 2 and recommended by Sussmann et al. (2011). Similar estimations using another set of four spectral intervals (see Sect. 2) have small differences from the results considered above. Average differences between the two sets of data are about 0.2 % for our measurements in Saint-Petersburg. Average deviation (similar to that in Table 2) of GOSAT version V02.xx CH_4 data from ground-base FTIR measurements using four spectral intervals is $\delta X_{CH_4} \sim -1.6$ ppb, and its standard deviation $n \sim 15.6$ ppb.

4 Discussion

Morino et al. (2011) made a comparison of the GOSAT version V01.xx and FTIR spectroscopic X_{CH_4} measurements in years 2009–2010 at 9 stations of ground-based TCCON network at latitudes from 45° S to 53° N. They found a systematic underestimation of satellite methane mole fractions with $\delta X_{CH_4} \approx -20 \pm 19$ ppb (-1.2 ± 1.1 %). Determinations of deviations between the GOSAT V01.xx data and CH_4 aircraft measurements in the troposphere gave δX_{CH_4} from -8 ± 10 ppb (Saitoh et al., 2012) to -39 ± 11 ppb (Tanaka et al., 2012). Values δX_{CH_4} for GOSAT version V01.xx data in Tables 1 and 3 falls within the specified ranges, with the mean and median $\delta X_{CH_4} \approx -13 \pm 26$ ppb. This may be an indirect indication that optical X_{CH_4} obtained from the Earth's surface near Saint-Petersburg are compatible with methane column mole fractions measured with the TCCON network.

Several algorithms for X_{CH_4} retrieval from GOSAT data were compared recently with ground-based FTIR spectroscopic observations. Parker et al. (2011) compared GOSAT X_{CH_4} measurements with data from TCCON network and with results of numerical modeling. They estimated relative deviations of individual satellite measurements to be ~0.1–0.9 % depending on latitude. Notholt et al. (2012) analyzed several different algorithms of methane retrievals and obtained standard deviations of differences between GOSAT and ground-based X_{CH_4} values in the range of 0.8–4 %. Schepers et al. (2012) studied influence of radiation scattering and cirrus clouds and obtained average differences between GOSAT and ground-based FTIR X_{CH_4} as low as −0.3 or −0.4 %. Butz et al. (2011) also showed existence of systematic biases of −0.3 %.

Yoshida et al. (2013) made comparisons of the GOSAT version V02.xx data with observations at TCCON ground-based network and found average biases of −5.9 ppb (−0.3 %) and standard deviations of 12.6 ppb (0.7 %). Our analysis of methane mole fraction from the GOSAT data version V02.xx (see Tables 2, 3 and Fig. 2) showed individual deviations between satellite and ground-based values in the range 0.01–1.8 % and the average differences about 0.2 ± 0.8 %. Some differences from estimations by Yoshida et al. (2013) may be caused by substantial statistical errors (because of limited number of measurements at Saint-Petersburg). However, the magnitudes of average deviations in Tables 2 and 3 show that Saint-Petersburg FTIR observations using the retrieval algorithms from the NDACC network could give reasonable agreement with the GOSAT satellite data. Standard deviation of δX_{CH_4} values in Table 2 is 15.1 ppb (about 0.9 %), which is compatible with compound errors of both types of measurements and is slightly larger than the value 12.6 ppb obtained by Yoshida et al. (2013).

Tables 1–3 show substantial standard deviations of ground-based FTIR X_{CH_4} values (up to 16–17 ppb). One should keep in mind that these measurements are carried out near the Saint-Petersburg megalopolis, so the total methane variability there might be higher than that for background measurements. Makarova et al. (2006) estimated that emission from Saint-Petersburg may contribute up to 2 % to the overall CH_4 column content. This enhanced variability of X_{CH_4} near Saint-Petersburg may contribute to some differences in average δX_{CH_4} and their standard deviations obtained in the present paper compared to the estimations by Yoshida et al. (2013).

In our study, we compared X_{CH_4} measured with GOSAT in ±3° latitude and longitude vicinity of the ground-based observation site. We also tried to use ±1° and ±5° co-location criteria. In these cases, we obtained the same orders of magnitude for biases between ground-based and satellite measurements as those in Tables 1–3.

Comparisons of ground-based and satellite FTIR methane mole fraction measurements do not take into account some characteristics that may influence the

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measurements and data processing, for example, differences in averaging kernels of remote sensing methods (Parker et al., 2011), or uncertainties in the parameters of fine structure of spectral lines (Chesnokova et al., 2011). Also due to a relatively small amount of sunny days for FTIR measurements near Saint- Petersburg, we should consider the present comparison as preliminary.

5 Conclusions

We compared the average over atmospheric column methane mole fractions, measured with FTIR spectroscopy from the Earth's surface at the Peterhof campus of Saint Petersburg State University (59.9° N, 29.8° E) in years 2009–2012 with similar observations with the Japanese GOSAT satellite (data versions V01.xx and V02.xx). Average difference between the GOSAT data version V01.xx and ground-based FTIR measurements from the Earth's surface is $\delta X_{CH_4} \approx -13$ and their standard deviation ~ 26 ppb, which is consistent with literature data about comparisons of this version of GOSAT data with the network of ground-based FTIR stations TCCON and with airplane in-situ measurements. The same average differences for the GOSAT data version V02.xx are smaller ($\delta X_{CH_4}/X_{CH_4} \approx 0.2\,\%$) and show that Saint-Petersburg FTIR observations could provide reasonable agreement with satellite data. Standard deviation of δX_{CH_4} values is 15.1 ppm (about 0.9 %), which is compatible with combined errors of both types of measurements. Relatively small amount of sunny days for FTIR measurements near Saint Petersburg requires further accumulation of the data of ground-based and satellite FTIR measurements and their comparisons.

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Table 1. Daily average values of CH_4 mole fractions for matching dates of ground-based FTIR measurements near Saint-Petersburg and GOSAT data version V01.xx. VMR units are ppb.

Date	$X_{CH_4\_spb}$	$X_{CH_4\_gos}$	δX_{CH_4}	$\delta X/X,\%$
2009-04-08	1797.4	1759.6	−37.8	−2.10
2009-04-22	1767.3	1724.1	−43.2	−2.44
2009-04-26	1769.5	1758.7	−10.7	−0.61
2010-04-12	1755.3	1767.6	12.3	0.70
2010-04-15	1744.0	1755.5	11.6	0.66
2010-07-11	1754.9	1776.6	21.7	1.24
2011-04-25	1775.6	1750.2	−25.5	−1.43
2011-09-04	1787.9	1742.5	−45.3	−2.53
2011-09-06	1778.7	1778.2	−0.5	−0.03
Average	1770.1	1757.0	−13.0	−0.73
Median	1769.5	1758.7	−10.7	−0.61
StDev	17.0	16.9	25.8	1.46

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Table 2. Same as Table 1, but for the GOSAT data version V02.xx.

Date	$X_{CH_4\_spb}$	$X_{CH_4\_gos}$	δX_{CH_4}	$\delta X/X$,%
2009-07-01	1768.3	1777.2	9.0	0.51
2009-08-21	1778.8	1779.5	0.7	0.04
2010-04-12	1755.3	1786.1	30.7	1.75
2010-04-15	1744.0	1772.9	28.9	1.66
2010-05-12	1804.4	1783.3	−21.1	−1.17
2010-05-20	1774.9	1783.8	8.8	0.50
2010-05-21	1777.1	1789.5	12.5	0.70
2010-06-28	1792.2	1777.7	−14.5	−0.81
2010-07-05	1793.5	1795.2	1.8	0.10
2010-07-06	1792.2	1788.7	−3.5	−0.19
2010-07-12	1754.9	1778.7	23.8	1.36
2010-07-14	1770.2	1784.5	14.4	0.81
2012-05-01	1782.2	1776.7	−5.5	−0.31
2012-06-20	1796.2	1784.7	−11.5	−0.64
2012-06-21	1802.3	1783.4	−18.9	−1.05
2012-06-30	1790.3	1792.9	2.6	0.14
2012-07-06	1790.2	1795.4	5.1	0.29
2012-07-27	1778.9	1781.9	3.0	0.17
Average	1780.3	1784.0	3.7	0.21
Median	1780.5	1783.6	2.8	0.16
StDev	16.9	6.5	15.1	0.85

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Table 3. Average characteristics for the data shown in Fig. 2. VMR units are ppb. априорный.

Data	Characteristic	$X_{CH_4\_SPB}$	$X_{CH_4\_GOS}$	δX_{CH_4}
V01.xx	Average	1774.6	1759.6	−15.0
	Median	1775.5	1759.6	−11.5
	StDEV	14.9	13.4	13.0
	N	23	23	23
V01.xx	Average	1779.3	1779.9	0.6
	Median	1780.3	1779.5	−0.1
	StDEV	16.0	10.9	14.7
	N	59	59	59

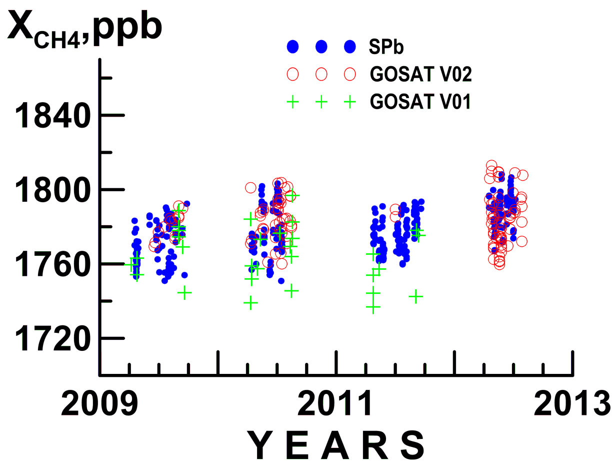

Fig. 1. Methane column mole fractions measured near Saint Petersburg and with GOSAT satellite (data version V01.xx and V02.xx).

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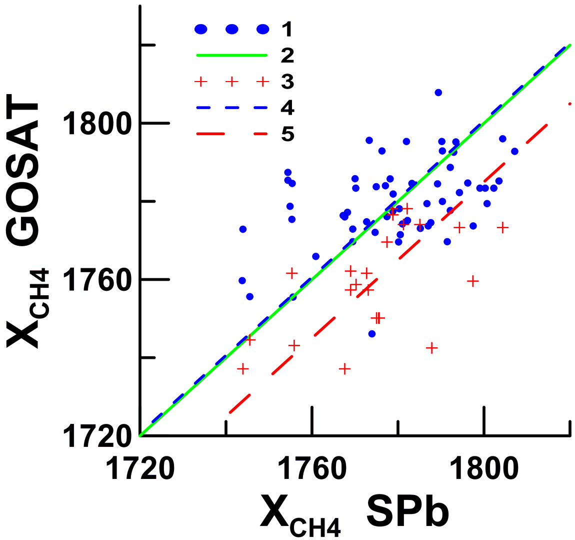

Fig. 2. Comparison of X_{CH_4} (in ppb) measured near St. Petersburg and with GOSAT satellite (data versions V01.xx – 3 and V02.xx – 1) when differences between the dates of measurements do not exceed two days. The line 2 corresponds to $X_{CH_4\_SPB} = X_{CH_4\_GOS}$, lines 4 and 5 are shifted from the line 2 by average δX_{CH_4} presented in Table 3 for GOSAT data versions V02.xx and V01.xx, respectively.

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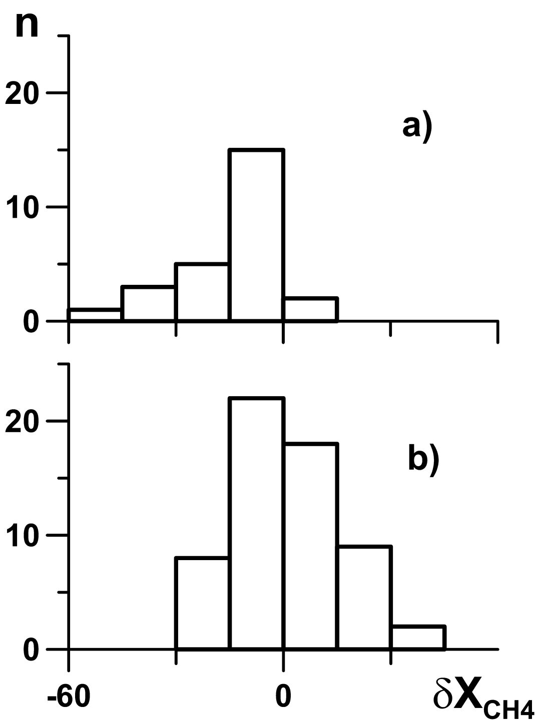

Fig. 3. Histograms of differences $\delta X_{CH_4} = X_{CO_2\_GOS} - X_{CO_2\_SPB}$ between pairs of measurements presented in Fig. 2 for GOSAT data version V01.xx **(a)** and V02.xx **(b)**.