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

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1 **Abstract**—The column-average mole fraction of methane measured with hyperspectral methods of ground-based Fourier transform spectroscopy at the Physical Department of St. Petersburg State University (59.9 N, 29.8 E) in 2009–2012 is compared with similar data measured from the Japanese GOSAT satellite. The average mole fraction of methane X_{CH_4} from GOSAT data version V01.xx are lower by 17–21 ppb than the corresponding value obtained from ground-based measurements with a standard deviation of about 13 ppb. For the GOSAT data version V02.xx, this difference is about 2 ppb on average, with a standard deviation of about 18 ppb. This corresponds to differences between data on X_{CH_4} from the GOSAT satellite and from the TCCON and NDACC networks.

Keywords: CH4, atmospheric methane, total content, ground-based measurements, FTIR spectroscopy, GOSAT satellite, comparison, validation

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INTRODUCTION

Methane is second most important anthropogenic greenhouse gas. Despite its low concentration in the Earth's atmosphere, it contributes about 15% of the greenhouse effect. A technique for surface or tropospheric air sampling and laboratory analysis with the use of aircrafts is usually used for local monitoring of methane (Conway et al., 2003). Optical spectrometry measuring techniques based on recording IR absorption spectra of solar radiation are used for measurements of the total atmospheric CH_4, column-average mole fraction of methane X_{CH_4}, or elements of the vertical distribution of methane.

Ground-based optical measurement data on X_{CH_4} can be useful for validation of satellite measurements, which also provide data on the total columnar CH_4. 1 Hyperspectral equipment is of growing use in these studies. To validate satellite monitoring data on greenhouse gases, a special International ground-based Total Carbon Column Observing Network (TCCON) 1 has been created; it uses hyperspectral Fourier Transform Spectrometer (FTS) measurements of direct IR solar radiation for calculating the total content of CO_2, CH_4, and other climate forcing gases (Wunch et al., 2011). Similar FTS measurements are also carried out at the international ground-based network for the Detection of Atmospheric Composition Change (DACC) (http://www.ndsc.ncep.noaa.gov/).

Spectroscopic measurements of the total content of methane were started at St. Petersburg State University (SPSU) in 1991 (Mironenkov et al., 1996; Makarova et al., 2009). Until 2009, they were carried out with the use of a IR solar spectrometer with a resolution of 0.4–0.6 cm^{-1}. Since 2009, ground-based hyperspectral FTS measurements have been carried 1 out with the use of a Bruker IFS 125 HR interferometer with a high spectral resolution. The measurement results for trace gases are described in (Poberovskii et al., 2010; Virolainen et al., 2011; Polyakov et al., 2011; Yagovkina et al., 2011).

The first global satellite data on the total columnar methane were obtained with the use of an IMG/ADEOS instrument; it measured outgoing thermal radiation with a high spectral resolution (Kobayashi et al., 1999). Further, CIAMACHY, AIRS, IASI, and TES instruments were used for the studies (Sussmann et al., 2005; Razavi et al., 2009; Xiong et al., 2010; Wecht et al., 2012). Despite wide observation programs, the geographical distribution of methane and its sources remain understudied (Solomon et al., 2007). Routine global satellite measurements ofCH_4 can help us to decide these problems.

The GOSAT (Global Greenhouse Gas Observation by Satellite) satellite was launched in January 2009. 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 monitoring of global distributions of the total 1 columnar CO_2 and CH_4 with the use of hyperspectral equipment. The column-average mole fractions of carbon dioxide X_{CO_2} and methane and X_{CH_4} are retrieved from near-IR data of a TANSO-FTS sensor of the Fourier spectrometer (Thermal And Near infrared Sensor for carbon Observations—Fourier Transform Spectrometer) mounted onboard the GOSAT satellite (Yoshida et al., 2011).

GOSAT data on X_{CO_2} and X_{CH_4} were preliminarily analyzed in (Morino et al., 2011) by comparison with ground-based TCCON measurements (see above). It was revealed that the satellite data are much lower than the ground-based measurement data. Further comparisons of X_{CO_2} and X_{CH_4} retrieved by other algorithms from GOSAT and TCCON data provided for better agreement between satellite and ground-based data (Notholt et al., 2012; Cogan et al., 2012). These comparisons were carried out for latitudes below 55° N; therefore, a joint analysis of satellite (GOSAT) and ground-based observations in higher latitudes with the use of different retrieve algorithms is of interest.

1 GOSAT hyperspectral measurements of X_{CO_2} were compared with ground-based FTS observations in (Gavrilov and Timofeev, 2013). In this work, we compare similar data on X_{CH_4} measured near St. Petersburg at a latitude of about 60° N in 2009–2012.

DATA MEASUREMENT AND PROCESSING

Solar radiation spectra are measured in Peterhof (59.88° N, 29.82° E, 20 m above sea level), about 35 km southeastw of the center of St. Petersburg. Interferograms are recorded in conditions of clear sky or sufficient breaks in overcast. The measurements are usually carried out at an optical path difference of 180 cm, which corresponds to a spectral resolution of 0.005 cm^{-1}. The time of accumulation and averaging of ten interferograms, which are used for producing one spectrum, is about 12 min.

High-resolution spectra of direct solar radiation measured by Bruker IFS125 HR were interpreted (calculation of the total content of gases in the atmosphere) using the standard SFIT2 v 3.92 software (Pougatchev et al., 1995; Rinsland et al., 1998; Hase et al., 2004) developed for the NDACC network. The SFIT2 algorithm uses the statistical regularization method with the Newton iteration method for calculation of gas content in the atmosphere. The HITRAN-2004 database (Rothman et al., 2005) is used as a source of data on parameters of the fine structure of molecular absorption lines.

The main input data for SFIT2 are the solar radiation spectrum measured, the optical path difference and instrument aperture, the solar angle, the signal-to-noise ratio, weather data (temperature and pressure profiles during the day of measurements), and *a priori* data on profiles of the mole fractions of gases. The weather data (temperature and pressure profiles) required for the spectra processing are received from the radio sounding station of the Main Geophysical Observatory (Voyeykovo vil.) (see, e.g., Weather Web, 2013), which is 50 km from Peterhof. Profiles of atmospheric gas concentrations calculated with the WACCM model (Whole Atmosphere Community Climate Model) (Garcia et al., 2007) specially for the Peterhof monitoring station (the corresponding latitude, longitude, and altitude above sea level) were used as the *a priori* profiles.

To retrieve the total columnar CH_4, the IR spectral ranges usual for the NDACC network are used (see, e.g., Sepulveda et al., 2012): 2613.7–2615.4, 2650.6–2651.3, 2835.5–2835.8, and 2903.6–2904.03 cm^{-1}. The average signal-to-noise ratio is about 800 in the above spectral ranges after rejecting spectra.

Random relative errors of a single measurement do not exceed 0.5% (according to estimates where the error matrix is calculated within the statistical regularization method implemented in the SFIT2 algorithm). Variations in X_{CH_4} usually do not exceed 1% under conditions of stable operation of the equipment and stable state of the atmosphere.

COMPARISON RESULTS

Periods of simultaneous ground-based and GOSAT measurements near St. Petersburg in 2009–2012 were chosen for the comparison of data on X_{CH_4}. Values of X_{CH_4} measured from the GOSAT satellite in a vicinity of ±3° h in latitude and longitude from the site of ground-based measurements were chosen from the NIES database (2012) for these time periods. Ground-based values of X_{CH_4} used for the comparison were measured at minimal solar angles (usually within ±3 h from local midday). The values falling in a 95% confidence interval near the average for a corresponding observation period were used. Since the satellite values of X_{CH_4} were measured for dry atmosphere, the ground-based values were also corrected for dry atmosphere using the data of reanalysis of weather information of the European ECMWF center (Dee et al., 2011).

Figure 1 shows individual values of X_{CH_4} from ground-based and satellite measurements. In many cases, dates of measurements with these two methods do not coincide. However, Figure 1 shows GOSAT V01.xx data systematically lower as compared to the ground-based data measured near St. Petersburg. For a more detailed analysis, pairs of individual ground-based and satellite values of $X_{CH_4\_SPB}$ and $X_{CH_4\_GOS}$ for which the dates of measurements differ by no more than 2 days were selected. Figure 2 shows the corresponding pairs of $X_{CH_4\_SPB}$ and $X_{CH_4\_GOS}$ for both ver-

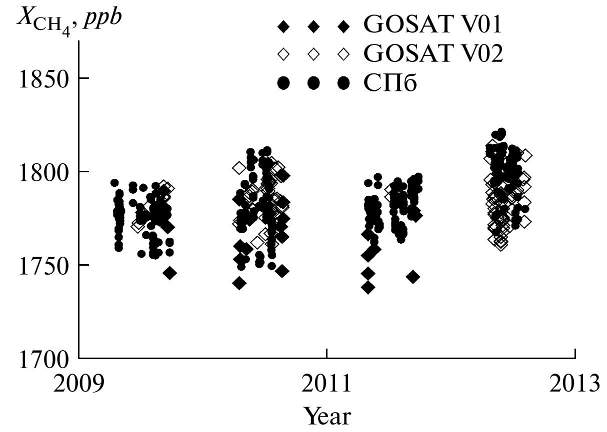

Fig. 1. Column-average mole fractions of methane (in ppb) measured from GOSAT (V01.xx and V02.xx versions) and from the ground near St. Petersburg.

sions of GOSAT data. The solid line in Fig. 2 corresponds to $X_{\mathrm{CH_4\_SPB}} = X_{\mathrm{CH_4\_GOS}}$. It can be seen that almost all values of $X_{\mathrm{CH_4}}$ for GOSAT V01.xx data lie above the solid line, i.e., $X_{\mathrm{CH_4\_SPB}} > X_{\mathrm{CH_4\_GOS}}$. The values of $X_{\mathrm{CH_4}}$ for GOSAT V02.xx data are distributed more symmetrically about the solid line. The coefficient of correlation between $X_{\mathrm{CH_4\_SPB}}$ and $X_{\mathrm{CH_4\_GOS}}$ are 0.65 and 0.71 for GOSAT V01.xx and GOSAT V02.xx data, respectively, in Fig. 2. The averages and variances for ground-based and satellite data shown in Fig. 2 are tabulated. The long and short dashed lines in Fig. 2 are shifted relative to the solid line according to $\delta X_{\mathrm{CH_4}} = X_{\mathrm{CH_4\_GOS}} - X_{\mathrm{CH_4\_SPB}}$ from the Table for GOSAT V01.xx and V02.xx data, respectively.

The differences $\delta X_{\mathrm{CH_4}}$ are mainly negative (to −59 ppb, or ~3.3%) for GOSAT V01.xx data. The corresponding average and median $\delta X_{\mathrm{CH_4}} \sim -(17\text{–}21)$ ppb, and the variance is ~13 ppb in the Table, i.e., $X_{\mathrm{CH_4}}$ values according to GOSAT V01.xx data are lower by about 1–1.3% than the ground-based FTS data.

Deviations of GOSAT V02.xx data on $\delta X_{\mathrm{CH_4}}$ from the ground-based measurement data have different signs in different days and vary from −26 ppb (1.5%) to 24 ppb (1.4%), which is about two times lower than the corresponding deviations for V01.xx data (see above). The relative deviations for GOSAT V02.xx data are lower than 1% in most cases. The corresponding average and median differences in the Table are $\delta X_{\mathrm{CH_4}}$ ppb (or about 0.1%), and the variance is ~18 ppb, or about 1%. In this case, the variability (variance) of the mole fraction of methane according to GOSAT V02.xx data is much lower (~11 ppb) than according to the ground-based measurements (~19 ppb) in the Table.

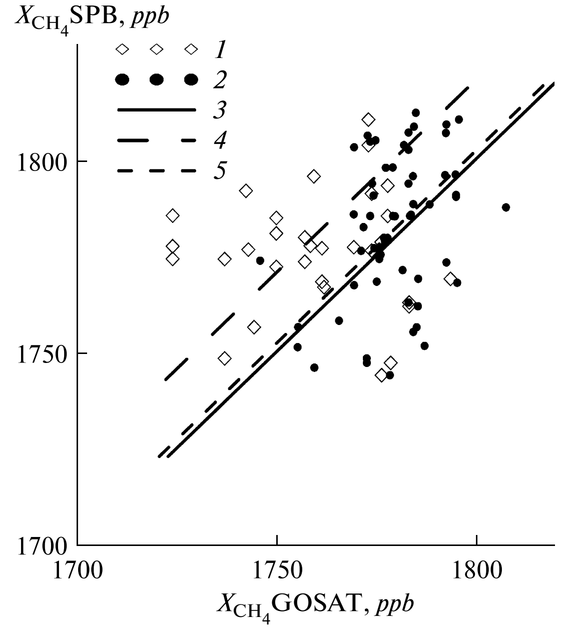

Fig. 2. Comparison of pairs of $X_{\mathrm{CH_4}}$ values (in ppb) measured from the ground near St. Petersburg and from GOSAT V01.xx (*1*) and V02.xx (*2*), the dates of measurements for which differ by no more than two days; $X_{\mathrm{CH_4\_SPB}} = X_{\mathrm{CH_4\_GOS}}$ (curve *3*), and curves *4* and *5* are shifted from curve *3* according to the average values of $\delta X_{\mathrm{CH_4}}$ from the Table for GOSAT V01.xx and V02.xx data versions, respectively.

The analysis of the histogram of differences $\delta X_{\mathrm{CH_4}}$ between pairs of ground-based and satellite measurements has shown that these differences are distributed almost symmetrically relative to zero for GOSAT

Average parameters (in ppb) for data in Fig. 2

Data	Parameter	$X_{\mathrm{CH_4\_SPB}}$	$X_{\mathrm{CH_4\_GOS}}$	$\delta X_{\mathrm{CH_4}}$
V01.xx	Average	1780.2	1759.6	−20.6
	Median	1777.8	1759.6	−17.2
	Variance	14.0	13.4	13.3
V02.xx	Average	1782.1	1779.9	−2.2
	Median	1785.5	1779.5	−1.8
	Variance	18.9	10.9	18.1

V02.xx data, while they show systematic underestimation of X_{CH_4} for GOSAT V01.xx as compared to ground-based FTS measurements.

DISCUSSION

Morino et al. (2011) compared the GOSAT V01.xx data and FTS measurement data on X_{CH_4} in 2009–2010 from nine TCCON stations at latitudes from 45° S to 53° N and revealed systematic underestimation in the satellite data X_{CH_4} ppb (–1.2 ± 1.1%). Close results have been obtained during the study of deviationsδX_{CH_4} between the GOSAT V01.xx data and aircraft measurements in the troposphere: from –8 ± 10 ppb (Saitoh et al., 2012) to –39 ± 11 ppb (Tanaka et al., 2012). Let us note that the median and average values$\delta X_{CH_4} \approx$ ppb for GOSAT V01.xx in the Table fall in these ranges. This can indirectly witnesses that ground-based FTS measurements of X_{CH_4} near St. Petersburg agree with the TCCON-measured columnar fraction mole of methane.

GOSAT data on X_{CH_4} retrieved with several algorithms in different works were compared with ground-based FTS measurements. Values of X_{CH_4} measured by the GOSAT satellite were compared with the TCCON data and with numerical simulation results in (Parker et al., 2011). It has been found that relative differences between individual satellite and ground-based measurements vary within the limits 0.1–0.9% depending on latitude. Different algorithms for methane retrieval were analyzed in (Notholt et al., 2012), and variances of differences between the GOSAT and ground-based values were found within the range 0.8–4%. Average differences between GOSAT and ground-based data on X_{CH_4} were found within the limits from –0.3 to –0.4% in (Schepers et al., 2012) during the study of light scattering and cirrus effects on FTS results. Systematic errors of ~–0.3% were found in (Butz et al., 2011). Unfortunately, the authors of the above works dud not use GOSAT data of V01.xx and V02.xx versions. Therefore, it is difficult to compare these results with the results of this work directly.

Our analysis of the mole fraction of methane from GOSAT V02.xx data (see the Table and Fig. 2) has shown that differences between satellite and ground-based values are within the limits 0.01–1.6% at an average deviation of ~–0.1 ± 0.9%. Though these average differences have significant variances (due to the limiting number of measurements), orders of their magnitudes show that FST observations near St. Petersburg agree well with the GOSAT data. Variances of variations in δX_{CH_4} shown in the Table are of ~13–18 ppm, or ~0.7–1%, and are compared with total errors of the both types of measurements.

Let us note that the variance of the ground-based X_{CH_4} values is quite high, ~14–19 ppb (see the Table). It should be taken into account that our measurements are carried out immediately near the megalopolis of St. Petersburg; therefore, the total variability of methane can be higher than in background regions. According to the estimations (Makarova et al., 2006), anthropogenic emission in St. Petersburg can contribute up to 2% of the total columnar CH_4.

The comparison performed between ground-based and satellite FTS measurements of the mole fraction of methane X_{CH_4} does not consider some parameters that can affect the measurement results and data processing, e.g., differences in averaging kernels of the remote sounding techniques used (Parker et al., 2011) or uncertainties in parameters of the fine structure of spectral lines (Chesnokova et al., 2011). In addition, the relatively small number of sunny days for FTS measurements near St. Petersburg requires further data accumulation for a more reliable comparison between satellite and ground-based measurements of atmospheric methane.

CONCLUSIONS

In this work, we have analyzed data received with the use of hyperspectral satellite and ground-based 1 instruments. The column-average mole fractions of methane X_{CH_4} FTS measured from the Japanese GOSAT satellite (V01.xx and Vo2.xx data versions) are compared with the data measured from the Earth's surface at the Physical Department of St. Petersburg State University (59.9 N, 29.8 E) in 2009–2012. The average and median differences in the GOSAT data version V01.xx and ground-based FTS measurements $\delta X_{CH_4} \approx -(17–21)$ ppb, and their variances are ~13 ppb, which agrees with literature data on the comparison of this version of GOSAT data with the TCCON data and with the results of analysis of airborne samples of tropospheric air. The average differences for the GOSAT V02.xx data are lower ($\delta X_{CH_4}/X_{CH_4} \approx 0.1\%$) and show that FST observations near St. Petersburg can provide for acceptable agreements with refined satellite data. The variances δX_{CH_4} ~ 13–18 ppb (~0.7–1%) correspond to the total errors of ground-based and satellite measurements. For a more reliable comparison between ground-based and satellite measurements, further accumulation of FTS data is required.

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SPELL: 1. hyperspectral