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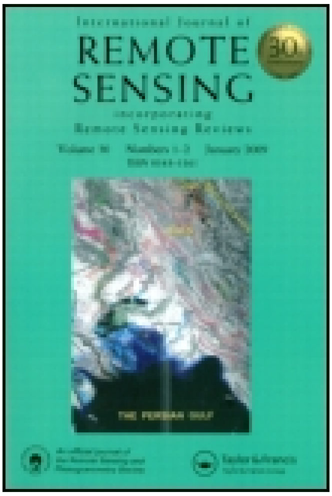

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Comparisons of satellite (GOSAT) and ground-based spectroscopic measurements of CH_4 content near Saint Petersburg: influence of data collocation

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We compared atmospheric column average mole fractions of methane measured with ground-based Fourier transform spectroscopy at the Physical Department of Saint Petersburg State University (59.9° N, 29.8° E) in years 2009–2012 with similar data obtained from the Japanese Greenhouse Gases Observing Satellite (GOSAT) satellite. For the GOSAT data version V02.xx, average and median values of biases between satellite and ground-based methane mole fractions are −(1.7–4.1) ppb and their standard deviations are 10–13 ppb. These values are similar to biases between the GOSAT satellite and the ground-based Total Carbon Column Observation Network and Network for the Detection of Atmospheric Composition Change making Fourier transform spectroscopic observations. Average and median biases for satellite data selected within $\alpha = \pm 1°$ latitude–longitude vicinity from the ground-based observations site are smaller than those for $\alpha = \pm 3°$ and $\alpha = \pm 5°$.

1. Introduction

Methane is an important anthropogenic greenhouse gas (e.g. Kondratyev and Varotsos 1995). Despite its low concentration in the Earth's atmosphere, the methane contribution to the anthropogenic greenhouse effect is ~15%. For local methane monitoring, laboratory analyses of air samples are typically used to determine CH_4 mole fractions near the Earth's surface and in the troposphere using aircraft (Conway et al. 2003). Optical spectrometer methods of measurements, based on registration of IR absorption spectra of solar radiation, are also applied to identify the total CH_4 contents and average mole fractions X_{CH_4} in the atmospheric column.

Ground-based optical measurements of methane can be useful for validating satellite measurements, which also provide information about total CH_4 contents in the atmospheric column. To test satellite observations of greenhouse gases, an international ground-based network TCCON (the Total Carbon Column Observing Network) was developed, which uses Fourier transform (FT) spectrometers measuring direct solar infrared (IR) radiation to determine total column contents of CO_2, CH_4, and other climate-forming gases (Wunch et al. 2011). Similar FTIR measurements are also performed at the international ground-based network NDACC (Network for the Detection of Atmospheric Composition Change, see http://www.ndsc.ncep.noaa.gov/).

In Saint Petersburg State University (SPbU), spectroscopic measurements of total methane were started in 1991 (Mironenkov, Poberovsky, and Timofeev 1996). These

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*Corresponding author. Email: gavrilov@pobox.spbu.ru measurements up to 2009 were carried out using a solar thermal spectrometer with resolution of 0.4–0.6 cm^{-1}. From January 2009 onwards, the Atmospheric Physics Department of SPbU has been conducting FTIR measurements using a Bruker IFS 125 HR interferometer with high spectral resolution up to 0.002 cm^{-1}. Similar interferometers are used at the NDACC network sites. These measurements of atmospheric trace components are described, for example, by Poberovsky et al. (2010), Virolainen et al. (2011), and Polyakov et al. (2011).

The first global satellite data on the total content of methane in the atmospheric column were obtained using the IMG/Advanced Earth Observing Satellite device, which measured outgoing atmospheric thermal radiation with high spectral resolution (Kobayashi et al. 1999). Further studies were conducted with the SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography), AIRS (Atmospheric Infrared Sounder), IASI (Infrared Atmospheric Sounding Interferometer) and TES (Tropospheric Emission Spectrometer) instruments (Sussmann et al. 2005; Razavi et al. 2009; Xiong et al. 2010; Wecht et al. 2012). Despite the extensive observational programme, geographical distributions of methane and its sources are not sufficiently clarified (Solomon 2007). Regular global satellite measurements of CH_4 can help us in studying global methane climatology.

In January 2009, the GOSAT (Greenhouse Gases Observing Satellite) satellite was launched, which is a joint project of the Japan Aerospace Exploration Agency, Ministry of the Environment, and the National Institute for Environmental Studies in Tsukuba, Japan (Kuze et al. 2009). The satellite is designed for space-based monitoring of the global distributions of total column CO_2 and CH_4 in the atmosphere. The average column mole fractions of carbon dioxide X_{CO_2} and methane X_{CH_4} are recovered from the data of the TANSO-FTS (Thermal and Near Infrared Sensor for Carbon Observation Fourier Transform Spectrometer) instrument for measurements of greenhouse gases on board of GOSAT (Yoshida et al. 2011).

Morino et al. (2011) and Yoshida et al. (2013) have performed comparisons of X_{CH_4} and X_{CO_2} obtained from the GOSAT satellite with measurements at the ground-based FTIR spectroscopy TCCON network (see above). Some algorithms for X_{CH_4} and X_{CO_2} retrieval from the GOSAT and TCCON data gave good agreement between satellite and ground-based measurements (Notholt et al. 2012; Cogan et al. 2012). Because these comparisons were made for latitudes below 55°, it is interesting to compare satellite (GOSAT) and ground-based observations at higher latitudes using a different recovery algorithm.

Gavrilov et al. (2013) made comparisons of the GOSAT satellite X_{CH_4} measurements with respective ground-based FTIR observations near Saint Petersburg. They used the GOSAT data obtained within ±3° latitude and longitude vicinity of the site of ground-based observations. In this paper, we continue the comparisons of X_{CH_4} measurements in years 2009–2012 in the vicinity of Saint Petersburg at a latitude of about 60° N. We select the GOSAT data for three different latitude and longitude vicinities (±5°, ±3°, ±1°) and study dependencies of the comparison results on the collocation of satellite and ground-based data.

2. Measurement and data processing

The FTIR measurements of solar radiation are performed near the Old Peterhof railway station (59.88° N, 29.82° E) at an elevation about 20 m above sea level, which is located about 35 km southwest from the centre of Saint Petersburg. Spectra registrations take place from a cloudless sky or sufficiently large breaks in cloud covers. Measurements typically use the optical path difference of 180 cm, which corresponds to the spectral resolution of 0.005 cm^{-1}. The time of accumulation and averaging of 10 individual recordings (to obtain a single spectrum) is about 12 min.

The determination of total column contents of gas species in the atmosphere from high-resolution solar radiation spectra measured with Bruker IFS125 HR uses version v.3.92 of the standard international SFIT2 software (Pougatchev, Connor, and Rinsland 1995; Rinsland et al. 1998; Hase et al. 2004), which has been developed for the NDACC network. The SFIT2 algorithm determines total column contents of atmospheric gases using statistical regularization by the Newton iterative method. As a source of information about the fine structure of molecular absorption lines, we used the HITRAN 2000 (with additions of 2001) database of spectroscopic line parameters (Rothmann et al. 2003).

The main input parameters for SFIT2 are as follows: measured spectrum of solar radiation, optical path difference, the device aperture, solar zenith angle, signal-to-noise ratio, meteorological data (temperature and pressure profiles during the day of measurements), and *a priori* information on the profiles of gas mole fractions. Weather information (temperature, pressure), required for spectral processing, comes from the upper air sounding station MGO-Voejkovo (e.g. Weather Web 2013), which is located about 50 miles (80 km) from Peterhof. *A priori* profiles of gas concentrations in the atmosphere have been calculated using the Whole Atmosphere Community Climate Model (Garcia et al. 2007) for the latitude, longitude, and altitude of the measurement station in Peterhof.

For the retrieval of total column CH_4 in the atmosphere, 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). Average values of the signal-to-noise ratio in the spectral bands are ~800.

Random relative errors of single $X_{\mathrm{CH_4}}$ measurements do not exceed 0.5% (estimated by the error matrix calculated within the statistical regularization method implemented in the SFIT2 program). In stable and steady-state conditions, variations of $X_{\mathrm{CH_4}}$ from atmospheric spectra measured in the course of a day usually do not exceed 1%. Gavrilov et al. (2013) described other details of the measurement technique.

3. The results of comparisons

To compare $X_{\mathrm{CH_4}}$ measured near Saint Petersburg at the Earth's surface with values obtained with the GOSAT satellite, we choose intervals of simultaneous measurements in 2009–2012. For these time intervals, we selected GOSAT version V02.xx values of $X_{\mathrm{CH_4}}$ from the database of the National Institute for Environmental Studies in Tsukuba, Japan (NIES 2012), which were measured in the $\pm\alpha$ latitude–longitude vicinity of the site of ground-based observations. In the present study, we use different widths of these vicinities: $\alpha = 5°$, $\alpha = 3°$, and $\alpha = 1°$. Ground-based $X_{\mathrm{CH_4}}$ values used for the comparisons were measured at lowest solar zenith angles (usually within ±3 hours from the local noon). In addition, we used only $X_{\mathrm{CH_4}}$ values that fall in the 95% confidence intervals about the mean values for the corresponding periods of observations. Since the satellite $X_{\mathrm{CH_4}}$ values are obtained for dry atmosphere (excluding water vapour), ground-based $X_{\mathrm{CH_4}}$ were also calculated for the dry atmosphere using the data of reanalysis of meteorological information from the ECMWF (European Centre for Medium-Range Weather Forecasting) (Dee et al. 2011).

For comparisons, we selected pairs of ground-based $X_{\mathrm{CH_4\_SPB}}$ and satellite $X_{\mathrm{CH_4\_GOS}}$ values, for which differences in dates of their measurements do not exceed 2 days. When we had several ground-based measurements during a day, we used the daily mean value for $X_{\mathrm{CH_4\_SPB}}$. For $X_{\mathrm{CH_4\_GOS}}$ we used individual satellite measurements selected for different latitude and longitude vicinities $\alpha = 5°$, $\alpha = 3°$, and $\alpha = 1°$.

Figure 1 presents X_{CH_4} values for ground-based and satellite measurements selected for different latitude–longitude vicinities. Figure 2 shows respective pairs of $X_{CH_4\_SPB}$ and $X_{CH_4\_GOS}$. The solid line in Figure 2 corresponds to $X_{CH_4\_SPB} = X_{CH_4\_GOS}$. Table 1 shows the average and median values, as well as standard deviations for ground-based and satellite data presented in Figure 2. The dashed line in Figure 2 is shifted by −3 ppb relative to the solid line, which corresponds to the average values of deviations $\delta X_{CH_4} = X_{CH_4\_GOS} - X_{CH_4\_SPB}$ presented in Table 1 for GOSAT data selected for latitude–longitude vicinities with different widths α.

Table 1 shows that for the GOSAT version V02.xx data the average and median values of δX_{CH_4} for different latitude–longitude vicinities are −(1.6–2.8) ppb, or −(0.1–0.2)%,

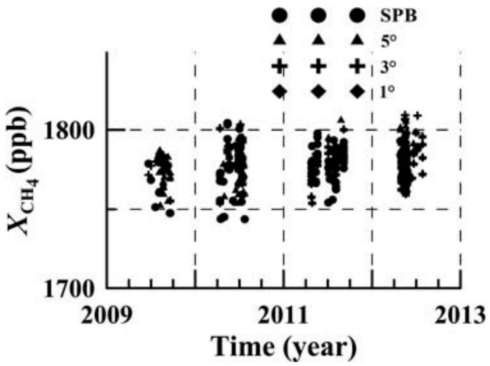

Figure 1. Average atmospheric column mole fractions of methane measured from the Earth's surface near Saint Petersburg and from the GOSAT satellite within α = 5°, α = 3°, and α = 1° latitude–longitude vicinities.

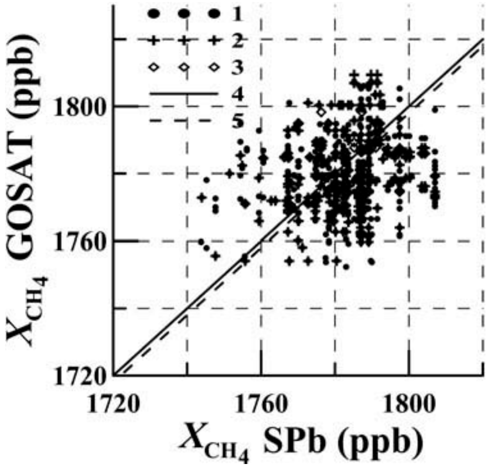

Figure 2. Comparisons of pairs of X_{CH_4} values measured from the ground near Saint Petersburg and from the GOSAT satellite within latitude–longitude vicinities α = 5° – 1, α = 3° – 2, and α = 1° – 3 for which differences between dates of measurement did not exceed 2 days. Line 4 corresponds to $X_{CH_4\_SPB} = X_{CH_4\_GOS}$, and line 5 is shifted from line 4 by −3 ppb in accordance with average values of δX_{CH_4} in Table 1.

Table 1. Average characteristics (in ppb) for the data presented in Figure 2.

Vicinity	$\alpha = 5°$			$\alpha = 3°$			$\alpha = 1°$		
Parameter	$X_{CH_4\_SPB}$	$X_{CH_4\_GOS}$	δX_{CH_4}	$X_{CH_4\_SPB}$	$X_{CH_4\_GOS}$	δX_{CH_4}	$X_{CH_4\_SPB}$	$X_{CH_4\_GOS}$	δX_{CH_4}
Average	1782.4	1780.0	−2.4	1783.2	1781.3	−1.9	1783.6	1781.9	−1.7
Median	1783.0	1779.2	−2.8	1783.6	1779.2	−2.4	1785.2	1784.6	−1.6
SD	12.1	11.6	15.4	11.1	9.8	14.5	10.2	8.4	13.0
N	506	506	506	256	256	256	60	60	60

and their standard deviations are (13–15) ppb, or less than 1%. Absolute values of δX_{CH_4} and their standard deviations tend to be smaller at $\alpha = 1°$ compared with that at larger α. Standard deviations of ground-based $X_{CH_4\_SPB}$ values are ~(10.2–12.1) ppb in Table 1, which are larger than the standard deviations of satellite $X_{CH_4\_GOS}$ values (8.4–11.6) ppb in Table 1.

Figure 3 shows the histograms of differences δX_{CH_4} between pairs of ground-based and satellite measurements for different latitude–longitude vicinities presented in Figure 2. One can see that the histograms in Figures 3(*b*) and (*c*) for $\alpha = 3°$ and $\alpha = 5°$ are shifted to negative δX_{CH_4}, while the histogram in Figure 3(*a*) for $\alpha = 1°$ is more symmetric. This corresponds to smaller absolute values of average and median δX_{CH_4} in Table 1 for $\alpha = 1°$ compared with wider latitude–longitude vicinities with larger α.

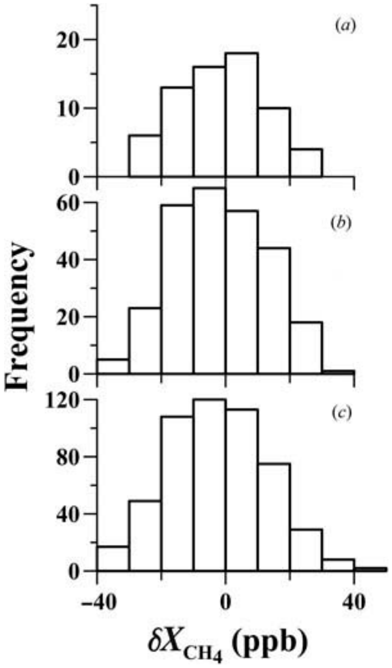

Figure 3. Histograms of differences $\delta X_{CH_4} = X_{CO_2\_GOS} - X_{CO_2\_SPB}$ between pairs of measurements presented in Figure 2 for different latitude–longitude vicinities $\alpha = 1°$ (*a*), $\alpha = 3°$ (*b*), and $\alpha = 5°$ (*c*).

4. Discussion

Gavrilov et al. (2013) made comparisons of X_{CH_4} measurements near Saint Petersburg with the GOSAT satellite data. For latitude–longitude vicinity $\alpha = 3°$, they found average and median values of δX_{CH_4} to be between −2.4 and 3 ppb depending on the selection of the GOSAT data for comparison. This shows that the results of comparisons of satellite and ground-based X_{CH_4} may depend on the methods used for data selection and their statistical processing. Comparisons of average and median values of δX_{CH_4} in Table 1 show their dependencies on the width of latitude–longitude vicinities α for data selection for the comparisons; the difference may reach 0.1%.

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 (see Table 1 and Figure 3) shows average and median deviations between satellite and ground-based values in the range −(0.1–0.2)%, which is about 0.1% smaller than the estimates by Yoshida et al. (2013). These differences may be partly caused by substantial statistical errors (because of the limited number of measurements obtained at Saint Petersburg). Gavrilov et al. (2013) also obtained smaller absolute values of average deviations between GOSAT and Saint Petersburg data.

The magnitudes of average and median values of differences δX_{CH_4} in Table 1 as well as comparisons by Gavrilov et al. (2013) show that Saint Petersburg FTIR observations using the retrieval algorithms from the NDACC network could be in reasonable agreement with GOSAT satellite data. Standard deviation of δX_{CH_4} values in Table 1 is 13–15 ppb (about 0.7–0.9%), which is compatible with compound errors of both types of measurements and corresponds to the value 12.6 ppb obtained by Yoshida et al. (2013). This may be indirect evidence that ground-based measurements in Saint Petersburg are consistent with measurements of the methane mole fractions at the TCCON network.

Values of X_{CH_4} obtained with GOSAT using several retrieval algorithms were compared with ground-based FTIR observations in various publications. Parker et al. (2011) compared the X_{CH_4} values measured by the GOSAT satellite with the ground-based TCCON network and with the results of numerical simulation. They found the relative differences of individual satellite and ground-based measurements to be within 0.1–0.9% depending on the latitude. Notholt et al. (2012), having analysed various methane recovery algorithms, obtained the standard deviations of differences between GOSAT and land values in the range from 0.8% to 4%. Schepers et al. (2012), when studying the effect of light scattering and Cirrus clouds on the FTIR spectroscopy, obtained average differences between GOSAT and ground-based X_{CH_4} between −0.3% and −0.4%. Butz et al. (2011) also showed the presence of systematic errors ~−0.3%. Results of Table 1 with average and median δX_{CH_4} values of −(0.1–0.2)% correspond to these estimates. This may indicate that FTIRS observations near Saint Petersburg are in reasonably good agreement with the GOSAT satellite data.

Note that the standard deviations of ground-based X_{CH_4} values are quite large ~10–12 ppb (see Table 1). One should take into account that our measurements were taken near the Saint Petersburg metropolis, so the variability of total methane there could be higher than that for background measurements. Makarova et al. (2006) estimated that anthropogenic emissions of Saint Petersburg could give contribution of up to 2% of the total CH_4 contents in the atmospheric column.

Comparisons of ground-based and satellite methane measurements conducted in this paper do not take into account some characteristics that may influence the results of measurement and data processing. For example, differences in the averaging kernels applied to remote-sensing techniques (Parker et al. 2011) or uncertainty in the parameters of the fine structure of spectral lines (Chesnokova et al. 2011). In addition, relatively small number of sunny days for FTIR measurements near Saint Petersburg requires further data accumulation for more reliable comparisons of satellite and ground-based measurements of atmospheric methane.

5. Conclusion

This study analysed data from satellite and ground-based FTIR instruments. We compared the average column mole fractions of atmospheric methane measured using the FTIR spectrometer on board the Japanese satellite GOSAT (data version V02.xx) and at the Earth's surface at the Atmospheric Physics Department of Saint Petersburg State University (59.9° N, 29.8° E) in 2009–2012. The average and median relative differences are −(0.1–0.2)% and indicate that FTIR observations near Saint Petersburg can provide an acceptable agreement with the GOSAT satellite data. The standard deviations of these differences 13–15 ppb (0.7–0.9%) match compound errors of ground-based and satellite measurements. Absolute average and median values of differences δX_{CH_4} for satellite data selected within the $\alpha = 1°$ latitude–longitude vicinity of the ground-based observation site are smaller than those for $\alpha = 3°$ and $\alpha = 5°$. More reliable comparisons of ground-based and satellite measurements require further accumulation of FTIR data.

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References

Butz, A., S. Guerlet, O. Hasekamp, D. Schepers, A. Galli, I. Aben, C. Frankenberg, J.-M. Hartmann, H. Tran, A. Kuze, G. Keppel-Aleks, G. Toon, D. Wunch, P. Wennberg, N. Deutscher, D. Griffith, R. Macatangay, J. Messerschmidt, J. Notholt, and T. Warneke. 2011. "Toward Accurate CO_2 and CH_4 Observations from GOSAT." *Geophysical Research Letters* 38: L14812. doi:10.1029/2011GL047888.

Chesnokova, T. Y., V. Boudon, T. Gabard, K. G. Gribanov, K. Firsov, and V. I. Zakharov. 2011. "Near-Infrared Radiative Transfer Modelling with Different CH_4 Spectroscopic Databases to Retrieve Atmospheric Methane Total Amount." *Journal of Quantitative Spectroscopy and Radiative Transfer* 112: 2676–2682. doi:10.1016/j.jqsrt.2011.08.005.

Cogan, A. J., H. Boesch, R. J. Parker, L. Feng, P. I. Palmer, J.-F. L. Blavier, N. M. Deutscher, R. Macatangay, J. Notholt, C. Roehl, T. Warneke, and D. Wunch. 2012. "Atmospheric Carbon Dioxide Retrieved from the Greenhouse Gases Observing Satellite (GOSAT): Comparison with Ground-Based TCCON Observations and GEOS-Chem Model Calculations." *Journal of Geophysical Research: Atmospheres* 117: D21301. doi:10.1029/2012JD018087.

Conway, T. J., A. E. Andrews, L. Bruhwiler, A. Crotwell, E. J. Dlugokencky, M. P. Hahn, and A. I. Hirsch. 2003. "Carbon Cycle Greenhouse Gases." *CMDL Report* 27: 32–57. http://www.esrl.noaa.gov/gmd/publications/annrpt27

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Andrae, B. G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. Van De Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hólm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A. P. McNally, B.M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. De Rosnay, C. Tavolato, J.-N.

Thépaut, and F. Vitart. 2011. "The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System." *Quarterly Journal of Royal Meteorological Society* 137: 553–597. doi:10.1002/qj.828.

Garcia, R. R., D. R. Marsh, D. E. Kinnison, B. A. Boville, and F. Sassi. 2007. "Simulation of Secular Trends in the Middle Atmosphere, 1950–2003." *Journal of Geophysical Research* 112: D09301. doi:10.1029/2006JD007485.

Gavrilov, N. M., M. V. Makarova, A. V. Poberovskii, and Y. M. Timofeev. 2013. "Comparisons of CH_4 Satellite GOSAT and Ground-Based FTIR Measurements near Saint-Petersburg (59.9°_N, 29.8° _E)." *Atmospheric Measurement Technique Discussion* 6: 1–22. doi:10.5194/amtd-6-1-2013.

Hase, F., J. W. Hannigan, M. T. Coffey, A. Goldman, M. Höpfner, N. B. Jones, C. P. Rinsland, and S. W. Wood. 2004. "Intercomparison of Retrieval Codes Used for the Analysis of High-Resolution Groundbased FTIR Measurements." *Journal of Quantitative Spectroscopy and Radiative Transfer* 87: 25–52. doi:10.1016/j.jqsrt.2003.12.008.

Kobayashi, H., A. Shimota, K. Kondo, E. Okumura, Y. Kameda, H. Shimoda, and T. Ogawa. 1999. "Development and Evaluation of the Interferometric Monitor for Greenhouse Gases: A High-Throughput Fourier-Transform Infrared Radiometer for Nadir Earth Observation." *Applied Optics* 38: 6801–6807. doi:10.1364/AO.38.006801.

Kondratyev, K. Y., and C. Varotsos. 1995. "Atmospheric Greenhouse Effect in the Context of Global Climate Change." *Il Nuovo Cimento C* 18 (2): 123–151. doi:10.1007/BF02512015.

Kuze, A., H. Suto, M. Nakajima, and T. Hamazaki. 2009. "Thermal and Near Infrared Sensor for Carbon Observation Fourier-Transform Spectrometer on the Greenhouse Gases Observing Satellite for Greenhouse Gases Monitoring." *Applied Optics* 48: 6716–6733. doi:10.1364/AO.48.006716.

Makarova, M. V., A. V. Poberovsky, I. S. Yagovkina, I. L. Karol, V. E. Lagun, N. N. Paramonova, A. I. Reshetnikov, and V. I. Privalov. 2006. "Study of Processes of Formation of Methane Fields in the Atmosphere of the Northwest Region of the Russian Federation." *Izvestia, Atmospheric and Oceanic Physics* 42: 237–249.

Mironenkov, A. V., A. V. Poberovsky, and Y. M. Timofeev. 1996. "Spectroscopic Measurements of the Methane in the Atmosphere Near St. Petersburg." *Izvestia, Atmospheric and Oceanic Physics* 32: 433–439.

Morino, I., O. Uchino, M. Inoue, Y. Yoshida, T. Yokota, P. O. Wennberg, G. C. Toon, D. Wunch, C. M. Roehl, J. Notholt, T. Warneke, J. Messerschmidt, D. W. T. Griffith, N. M. Deutscher, V. Sherlock, B. Connor, J. Robinson, R. Sussmann, and M. Rettinger. 2011. "Preliminary Validation of Column-Averaged Volume Mixing Ratios of Carbon Dioxide and Methane Retrieved from GOSAT Short-Wavelength Infrared Spectra." *Atmospheric Measurement Techniques* 4: 1061–1076. doi:10.5194/amt-4-1061-2011.

NIES. 2012. "Database of the GOSAT Project." *Courtesy JAXA/NIES/MOE*. https://data.gosat.nies.go.jp

Notholt, J., T. Blumenstock, D. Brunner, B. Buchmann, B. Dils, M. De Mazière, C. H. Popp, and R. Sussmann. 2012. "Product Validation and Algorithm Selection Report (PVASR)." *ESA Climate Change Initiative (CCI). Final Report*, August 22. http://www.esa-ghg-cci.org/?q=node/95

Parker, P., H. Boesch, A. Cogan, F. Fraser, L. Feng, P. I. Palmer, N. Deutscher, D. W. T. Griffith, J. Notholt, P. O. Wennberg, D. Wunch, and D. Wunch. 2011. "Methane Observations from the Greenhouse Gases Observing Satellite: Comparison to Ground-Based TCCON Data and Model Calculations." *Geophysical Research Letters* 38: L15807. doi:10.1029/2011GL047871.

Poberovsky, A. V., M. V. Makarova, A. V. Rakitin, D. V. Ionov, and Y. M. Timofeev. 2010. "Variability of Total Contents of Climatically Active Gases from Ground-Based High-Resolution Spectroscopic Measurements." *Doklady* 432: 257–259.

Polyakov, A. V., Y. M. Timofeev, A. V. Poberovsky, and I. S. Yagovkina. 2011. "Seasonal Variations of Total Content of Hydrogen Fluoride in the Atmosphere." *Izvestia, Atmospheric and Oceanic Physics* 47: 823–828.

Pougatchev, N. S., B. J. Connor, and C. P. Rinsland. 1995. "Infrared Measurements of the Ozone Vertical Distribution above Kitt Peak." *Journal of Geophysical Research* 100: 16689–16697. doi:10.1029/95JD01296.

Razavi, A., C. Clerbaux, C. Wespes, L. Clarisse, D. Hurtmans, S. Payan, C. Camy Peyret, and P. F. Coheur. 2009. "Characterization of Methane Retrievals from the IASI Space-Borne Sounder." *Atmospheric Chemistry and Physics* 9: 7889–7899. doi:10.5194/acp-9-7889-2009.

Rinsland, C. P., N. B. Jones, B. J. Connor, J. A. Logan, N. S. Pougatchev, A. Goldman, F. J. Murcray, T. M. Stephen, A. S. Pine, R. Zander, E. Mahieu, and P. Demoulin. 1998. "Northern and Southern Hemisphere Ground-Based Infrared Spectroscopic Measurements of Tropospheric Carbon Monoxide and Ethane." *Journal of Geophysical Research* 103: 28197–28217. doi:10.1029/98JD02515.

Rothmann, L. S., A. Barbe, D. C. Benner, L. R. Brown, C. Camy-Peyret, M. R. Carleer, K. Chance, C. Clerbaux, V. Dana, V. M. Devi, A. Fayt, J.-M. Flaud, R. R. Gamache, A. Goldman, D. Jacquemart, K. W. Jucks, W. J. Lafferty, J.-Y. Mandin, S. T. Massie, V. Nemtchinov, D. A. Newnham, A. Perrin, C. P. Rinsland, J. Schroeder, K. M. Smith, M. A. H. Smith, K. Tang, R. A. Toth, J. V. Auwera, P. Varanasi, and K. Yoshino. 2003. "The HITRAN Molecular Spectroscopic Database: Edition of 2000 Including Updates through 2001." *Journal of Quantitative Spectroscopy and Radiative Transfer* 82: 5–44. doi:10.1016/S0022-4073(03)00146-8.

Schepers, D., S. Guerlet, A. Butz, J. Landgraf, C. Frankenberg, O. Hasekamp, J. F. Blavier, N. M. Deutscher, D. W. T. Griffith, F. Hase, E. Kyro, I. Morino, V. Sherlock, R. Sussmann, and I. Aben. 2012. "Methane Retrievals from Greenhouse Gases Observing Satellite (GOSAT) Shortwave Infrared Measurements: Performance Comparison of Proxy and Physics Retrieval Algorithms." *Journal of Geophysical Research* 117: D10307. doi:10.1029/2012JD017549.

Solomon, S., ed. 2007. *The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Sussmann, R., F. Forster, M. Rettinger, and N. Jones. 2011. "Strategy for High-Accuracy-And-Precision Retrieval of Atmospheric Methane from the Mid-Infrared FTIR Network." *Atmospheric Measurement Techniques* 4: 1943–1964. doi:10.5194/amt-4-1943-2011.

Sussmann, R., W. Stremme, M. Buchwitz, and R. De Beek. 2005. "Validationof ENVISAT/SCIAMACHY Columnar Methane by Solar FTIR Spectrometry at the Ground-Truthing Station Zugspitze." *Atmospheric Chemistry and Physics* 5: 2419–2429. doi:10.5194/acp-5-2419-2005.

Virolainen, J. A., Y. M. Timofeyev, D. V. Ionov, A. V. Poberovsky, and A. M. Shalamyansky. 2011. "Ground-Based Measurements of Total Ozone with IR-Method." *Izvestia, Atmospheric and Oceanic Physics* 47: 521–532.

Weather Web. 2013. University of Wyoming, College of Engineering and Applied Science. http://weather.uwyo.edu.

Wecht, K. J., D. J. Jacob, S. C. Wofsy, E. A. Kort, J. R. Worden, S. S. Kulawik, D. K. Henze, M. Kopacz, and V. H. Payne. 2012. "Validation of TES Methane with HIPPO Aircraft Observations: Implications for Inverse Modeling of Methane Sources." *Atmospheric Chemistry and Physics* 12: 1823–1832. doi:10.5194/acp-12-1823-2012.

Wunch, D., G. Toon, J.-F. L. Blavier, R. A. Washenfelder, J. Notholt, B. J. Connor, D. W. T. Griffith, V. Sherlock, and P. O. Wennberg. 2011. "The Total Carbon Column Observing Network (TCCON)." *Philosophical Transactions of Royal Society* A369 (1943): 2087–2112.

Xiong, X., C. D. Barnet, Q. Zhuang, T. Machida, C. Sweeney, and P. K. Patra. 2010. "Mid-Upper Tropospheric Methane in the High Northern Hemisphere: Spaceborne Observations by AIRS, Aircraft Measurements, and Model Simulations." *Journal of Geophysical Research* 115: D19309. doi:10.1029/2009JD013796.

Yoshida, Y., N. Kikuchi, I. Morino, O. Uchino, S. Oshchepkov, A. Bril, T. Saeki, N. Schutgens, G. C. Toon, D. Wunch, C. M. Roehl, P. O. Wennberg, D. W. T. Griffith, N. M. Deutscher, T. Warneke, J. Notholt, J. Robinson, V. Sherlock, B. Connor, M. Rettinger, R. Sussmann, P. Ahonen, P. Heikkinen, E. Kyrö, J. Mendonca, K. Strong, F. Hase, S. Dohe, and T. Yokota. 2013. "Improvement of the Retrieval Algorithm for GOSAT SWIR XCO_2 and XCH_4 and Their Validation Using TCCON Data." *Atmospheric Measurement Techniques* 6: 1533–1547. doi:10.5194/amt-6-1533-2013.

Yoshida, Y., Y. Ota, N. Eguchi, N. Kikuchi, K. Nobuta, H. Tran, I. Morino, and T. Yokot. 2011. "Retrieval Algorithm for CO_2 and CH_4 Column Abundances from Short-Wavelength Infrared Spectra Observations by the Greenhouse Gases Observing Satellite." *Atmospheric Measurement Techniques* 4: 717–734. doi:10.5194/amt-4-717-2011.