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Aircraft measurements of carbon dioxide and methane for the calibration of ground-based high-resolution Fourier Transform Spectrometers and a comparison to GOSAT data measured over Tsukuba and Moshiri

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Abstract

Aircraft measurements of carbon dioxide and methane over Tsukuba (36.05° N, 140.12° E) (February 2010) and Moshiri (44.36° N, 142.26° E) (August 2009) were made to calibrate ground-based high-resolution Fourier Transform Spectrometers (g-b FTSs) and to compare with the Greenhouse gases Observing SATellite (GOSAT). The aircraft measurements over Tsukuba in February 2010 were successful in synchronizing with both the g-b FTS and GOSAT for the first time. Airborne in situ and flask sampling instruments were mounted on the aircraft and measurements were carried out between altitudes of 0.5 and 7 km to obtain vertical profiles of carbon dioxide (CO₂), methane (CH₄), and other gaseous species.

By comparing the g-b FTS measurements with the airborne measurements, the column-averaged dry air mole fractions of CO₂ (X_{CO_2}) and CH₄ (X_{CH_4}) retrieved from the g-b FTS measurements at Tsukuba were biased low by $0.33 \pm 0.11\%$ for X_{CO_2} and $0.69 \pm 0.29\%$ for X_{CH_4} . The g-b FTS values at the Moshiri were biased low by 1.24% for X_{CO_2} and 2.11% for X_{CH_4} . The GOSAT data show biases that are $3.1 \pm 1.7\%$ low for X_{CO_2} and $2.5 \pm 0.8\%$ low for X_{CH_4} than the aircraft measurement obtained over Tsukuba.

1 Introduction

Global warming by greenhouse gases is one of the most important environmental issues of our time. Atmospheric concentrations of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) have been increasing since the beginning of the industrial era as a result of human activities. CO₂, in particular, is an important greenhouse gas, second only to water vapor, and the global-averaged concentration of atmospheric CO₂ increased from 280 ppm in the pre-industrial era to 379 ppm in 2005 (IPCC, 2007). Increases in these greenhouse gases enhance a radiative forcing of the atmosphere and affect global climate change. An accurate prediction of the CO₂ concentration requires

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measurements for the quantification of the distribution and variability of CO₂ sources and sinks. Ground stations and tall towers with flask sampling and/or in situ instruments using Non-Dispersive InfraRed (NDIR) analyzers and cavity ringdown spectroscopy (Inoue and Matsueda, 2001; Winderlich et al., 2010) currently measure atmospheric CO₂ with high precision. In addition, ship- and aircraft-based measurements have been carried out, though less frequently. These measurements are precise but sparse, especially in Africa and South America. This sparseness causes large uncertainties in current estimates of the CO₂ sources and sinks (Gurney et al., 2001). Rayner and O'Brien (2001) established the required precision of monthly averaged column data better than 2.5 ppm for the total of atmospheric CO₂ data to be useful for reducing the uncertainties in regional (8° × 10° footprint) CO₂ source and sink estimations. The feasibility of a global measurement of CO₂ in the near-infrared region from space has been explored in the past (O'Brien and Rayner, 2002; Mao and Kawa, 2004). The authors determined that space-based measurements are one of the most effective tools for CO₂ source and sink estimations because of the wide spacial coverage they offer around the globe. The Greenhouse gases Observing SATellite (GOSAT) was developed jointly by the Japanese Ministry of the Environment (MOE), the National Institute for Environmental Studies (NIES), and the Japan Aerospace Exploration Agency (JAXA) to measure concentrations of CO₂ and CH₄ from space. After GOSAT was launched, it was placed in a sun-synchronous orbit at a 666-km altitude with a 3-day revisit time of around 12:50 LT (local time) (Yokota et al., 2009). The instruments onboard GOSAT are the Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer (TANSO-FTS) and the TANSO Cloud and Aerosol Imager (TANSO-CAI) (Kuze et al., 2009). TANSO-FTS measures the solar radiation reflected from the ground at three Short Wavelength InfraRed (SWIR) bands (0.76, 1.6, and 2.0 μm) and the emission from the ground and atmosphere at the wide Thermal InfraRed (TIR) band (5.5–14.3 μm) with a resolution of 0.2 cm⁻¹.

Space-based instruments have to be validated using other measurements, such as in situ or sampling measurements by aircraft and remote sensing measurements by

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ground-based high-resolution Fourier transform spectrometers (g-b FTS). Measuring direct sunlight with a g-b FTS is one of the most precise remote sensing techniques to derive the total column of atmospheric CO₂ under clear sky conditions (Washenfelder et al., 2003; Ohyama et al., 2009; Messerschmidt et al., 2010, 2011). The g-b FTS at Tsukuba is part of the Total Carbon Column Observing Network (TCCON) (Wunch et al., 2011) and is used to validate XCO₂ and XCH₄ retrieved from the GOSAT observation. The total column from space is directly validated by the total column measurement from the ground (i.e. the TCCON FTS instruments).

For this reason the g-b FTS at Tsukuba must be calibrated against an instrument with high-precision and accuracy obtained independently. For this work, we carried out aircraft measurements over Tsukuba and Moshiri. The purpose of these aircraft measurements is to calibrate the g-b FTS over Tsukuba and Moshiri and validate the GOSAT data. We installed hand-operated air sampling equipment (HSE) and continuous CO₂ measuring equipment (CME) on the aircraft in order to measure vertical profiles of CO₂ and CH₄. The column-averaged dry air mole fractions of CO₂ (XCO₂) and CH₄ (XCH₄) were calculated from the aircraft measurements to compare with those derived from the g-b FTSs and GOSAT. We describe the measurement instruments onboard the aircraft in Sect. 2. The details of the aircraft measurement and the ground sites are described in Sect. 3. The calculation of XCO₂ and XCH₄ from the aircraft profiles is presented in Sect. 4, and the results of the g-b FTS and GOSAT comparison with the aircraft measurements are discussed in Sect. 5.

2 Aircraft and instruments

2.1 Aircraft

The Beechcraft King Air 200T, operated by Diamond Air Service Inc., is a twin-turboprop aircraft with a pressurized cabin. We installed the CME for continuous CO₂ measurement and the HSE for CO₂, CH₄, and other gases. Typical durations were

1.7–2.3 h while spiral descent flights between 7 km and 0.5 km were carried out. The position (latitude, longitude, and ellipsoid height) of the aircraft was monitored by GPS and information of the outside temperature, static pressure, and ground speed was provided by the aircraft's instruments.

2.2 Hand-operated air sampling equipment (HSE)

The HSE is composed of Pyrex glass flasks and solenoid valves in a suitcase equipped with cushioning materials to reduce shocks by aircraft vibrations. Figure 1 shows a schematic diagram of the HSE instrument. Eight 750-ml glass flasks are enclosed in the case. The solenoid valves (SMC, SYJ314M-6LZ) were attached to both ends of the flask and actuated by high-pressure N₂ gas from a gas cylinder. An air inlet port was placed in a front-facing position at the top fuselage of the aircraft, and a stainless steel tube, used to flow air to the instruments, was placed in the aircraft. A diaphragm pump (Gast Manufacturing, Inc., MAA-P108-HB) was connected to the stainless steel tube to pressurize sample air into the flask. The procedure for sampling air in the atmosphere was done as follows: opening and closing actions for in/out solenoid valves at both ends of the flask were made by a valve controller. Sampling was started when the aircraft reached the desired altitude. First, both solenoid valves were left open to exchange the air inside the flask for 60 s. Then the solenoid valve (out) was closed to pressurize to 0.2 MPa in the flask for 45 s. Finally, the solenoid valve (in) was closed. After the flight, the HSE was unloaded from the aircraft and transported to NIES for high-precision analysis of the volume mixing ratios (VMRs) of CO₂, CH₄, CO, H₂, N₂O, and SF₆. The CO₂ concentration was analyzed with a NDIR analyzer (LI-COR, either LI-6252 or LI-6262) and a gas chromatograph equipped with a flame ionization detector (GC-FID; Agilent Technologies, HP-5890) was used to analyze CH₄. The same gas chromatograph with a reduction gas detector (Trace Analytical, RGD-2) was used to analyze CO and H₂. A gas chromatograph with an electron capture detector (GC-ECD; Agilent Technologies, HP-6890) was used for N₂O and SF₆ (Machida et al., 2008). The data from the NDIR and gas chromatographs were collected on the same

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PC. Analytical precisions are better than 0.03 ppm for CO₂, 1.7 ppb for CH₄, 0.3 ppb for CO, 3.1 ppb for H₂, 0.3 ppb for N₂O, and 0.3 ppt for SF₆. We prepared two sets of the HSE, so 16 samples were obtained in one flight.

2.3 Continuous CO₂ measurement equipment (CME)

The CME instrument measures CO₂ concentration continuously with a NDIR analyzer (LI-COR, LI-840) during the flight. Figure 2 shows a schematic diagram of the CME installed in the aircraft. The air inlet was placed together with that of the HSE. The air was drawn through the stainless steel tube and pressurized by a diaphragm pump (Gast Manufacturing, Inc., MAA-P108-HB). Sintered filters were inserted to remove fine particles. Prior to the analysis by the NDIR analyzer, the sampled air was dehumidified using a Naflon dryer and a chemical dryer (magnesium perchlorate). The flow rate is kept at 150 standard cc per minute (sccm) by a mass flow controller (HORIBA STEC, Co. Ltd., SEC-E40). The absolute pressure of the NDIR cell was kept constant (110 hPa) by an auto pressure controller (UR-7340RO-B) in the back of the NDIR cell. The inflow of the sampled air to the NDIR cell was switched to two standard gases of 380.89 ppm and 402.44 ppm for 150 s per 60 min. A programmable controller/data logger device (Campbell Scientific, CR1000) controlled the solenoid valves (Koganei, GA010E1) for switching the introduced gas and monitored measurement parameters, such as flow rate, cell pressure, and so on. Measured CO₂ concentrations by the NDIR analyzer were stored every 2 s in this device and were monitored by a notebook PC through an RS-232C connection. The standard gases were calibrated before the aircraft measurement against the CO₂ calibration scale at NIES by the gravitational method (NIES95 scale). The NIES95 scale was compared with the World Meteorological Organization Global Atmosphere Watch (WMO GAW) CO₂ standard scale at the National Oceanic and Atmospheric Administration, Climate Monitoring and Diagnostic Laboratory (NOAA, CMDL) in 1996 (Peterson et al., 1999). The differences in CO₂ and CH₄ between these scales (NIES-WMO) are 0.10 to 0.14 ppm in a range between 355 and 385 ppm and +4 to +5 ppb in a range between 1750 and 1838 ppb, respectively

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(Zhou et al., 2009) Switching to two standard gases by regular intervals (150 s per 60 min), analytical precision of the CME for the CO₂ concentration is within ±0.2 ppm for 10 s on average during the aircraft measurements.

3 Aircraft measurement and ground sites

5 The calibration with aircraft vertical profiles is necessary for the g-b FTS measurement to maintain high precision and accuracy. The aircraft measurements were carried out over Tsukuba (36.05° N, 140.12° E) and Moshiri (44.36° N, 142.26° E) at around 12:50 LT, which corresponds to GOSAT's overpass time. The g-b FTSs (Bruker IFS 120 HR) were operated at both sites. Vertical profiles of the meteorological parameters (pressure, temperature, relative humidity, wind speed, and wind direction) were measured with radio sondes around the aircraft measurements by the Japan Weather Association under contract with the NIES. Figure 3 shows the location of both observation sites. Tsukuba is 50 km northeast of Tokyo in the Kanto Plain and includes forests, agricultural lands, and urban areas. Tsukuba is one of the most important sites for validation of GOSAT data because in addition to the g-b FTS, several instruments are in operation, such as meteorological instruments, surface in situ measurements for CO₂ and CH₄, lidar, and a sky radiometer. CO₂ and CH₄ concentrations at 1.5, 25, 100, and 200 m altitudes from the ground were continuously observed at the meteorological tower of the Meteorological Research Institute (MRI), Tsukuba, Japan (Inoue and Matsueda, 2001). The Moshiri site is located in a mountainous forest region and can provide validation for GOSAT data recorded over different topography from those recorded over Tsukuba. The flight routes over both sites are described below.

During the flight over Tsukuba, the aircraft took off from Komaki Airport, Aichi, Japan. Air traffic control over Tsukuba is strict because of the controlled airspace for the Narita and Haneda international airports, so the flight over Tsukuba was restricted to altitudes below 2 km. Consequently, the altitudes from 7 km to 2 km were sampled over Kumagaya, about 70 km west of Tsukuba. The typical flight path performed on 14 February

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2010, is shown in Fig. 4. It illustrates the spiral descent flights over Tsukuba and Kugayama.

We also carried out an aircraft measurement on 26 August 2009, over the Moshiri observatory of the Geospace Research Center the Solar-Terrestrial Environment Laboratory of Nagoya University, which is located in northwestern Hokkaido. The Moshiri observatory, a GOSAT validation observational site, operates a g-b FTS and meteorological instruments. Tokachi-Obihiro Airport was used as base camp for the Hokkaido measurement. A descent spiral flight was made over Taiki to coincide with a GOSAT measurement on 30 August 2009. Because Taiki, located 200 km southeast of Moshiri, has a flat and almost homogeneous surface, it is suitable to compare the satellite measurement with the aircraft data. GOSAT did not successfully retrieve XCO_2 or XCH_4 due to clouds in its field of view on 30 August 2009.

4 Calculation of XCO_2 and XCH_4 from the aircraft measurement

To compare the values retrieved from the g-b FTS with those calculated from the aircraft profiles, CO_2 and CH_4 measured by the aircraft were combined using a priori profiles in GFIT, as described by Wunch et al. (2010). The GFIT algorithm, which was developed at the Jet Propulsion Laboratory (JPL) and is the software package used to produce all TCCON data, is a spectral fitting code to retrieve the column-averaged abundances of atmospheric trace gases from infrared solar absorption spectra (Wunch et al., 2011). The CO_2 a priori profile in GFIT for altitudes up to 10 km was taken from a climatology based on the GLOBALVIEW dataset (GLOBALVIEW-CO2 2006), and it varies based on the time of year and the latitude of the site. The stratospheric CO_2 profiles were generated from an age of air relationship derived by Andrews et al. (2001). The GFIT CH_4 a priori profiles were generated from balloon-borne MkIV FTS data (Toon, 1991). The CH_4 and HF volume mixing ratios are inversely correlated in the stratosphere (Luo et al., 1995; Washenfelder et al., 2003); therefore, this correlation can be applied to adjust the CH_4 profile in the stratosphere. However, since the g-b

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FTS instruments at Tsukuba and Moshiri do not measure the wavelength window containing the HF absorption, the correction using the CH₄-HF relationship could not be performed in this study. Instead, we make use of the temperature profile measured from a radio sonde during the aircraft overpasses to determine the difference between the measured tropopause altitude and that calculated in GFIT from the NCEP reanalysis temperature profile, and we adjust the CH₄ stratospheric profile accordingly.

Figures 5 and 6 show combined CO₂ and CH₄ profiles observed on 20 February 2010, over Tsukuba and Kumagaya. The red and blue dots are the aircraft data and the meteorological tower data at MRI, respectively. The gray lines show the combined ground, aircraft, and GFIT a priori profiles. For comparisons of XCO₂ and XCH₄ from aircraft profiles with those retrieved from the g-b FTS, averaging kernels of the g-b FTS measurements must be taken into account. The XCO₂ for the aircraft in situ profile weighted by the column averaging kernel *a* (Rodgers and Connor 2003) is calculated as follows:

$$X_{\text{CO}_2}^{\text{in situ}} = X_{\text{CO}_2}^{\text{a}} + \sum_j h_j a_j (t_{\text{in situ}} - t_{\text{a}})_j \quad (1)$$

where XCO₂^a is the column-averaged dry mole fraction for the a priori profile *t*_a, *h*_{*j*} is the pressure weighting function, and *t*_{in situ} is the in situ profile from the aircraft measurement. The XCH₄ is derived in the same way using Eq. (1).

5 Results and discussion

5.1 Comparison of the g-b FTSs and GOSAT with the aircraft measurement

The XCO₂ and XCH₄ values retrieved from the g-b FTS measurements at Tsukuba (2010) and Moshiri (2009) were compared with those calculated from the aircraft measurements. The g-b FTS data were corrected for an airmass-dependent artifact for

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XCO_2 and were calibrated with the TCCON common scaling factors empirically determined using aircraft profiles over many TCCON sites to place the TCCON data on the WMO standard reference scales (Wunch et al., 2010) for XCO_2 and XCH_4 . The GOSAT data (V01.20) were successfully retrieved over Tsukuba on 14, 20, and 23 February 2010, when the aircraft measurements were carried out. There are two types of GOSAT data: those for Research Announcement investigators (RA) and for general public users (GU). GU data are selected from RA data based on several criteria. The degrees of freedom for signals must be larger than unity, the mean squares of the residual spectra must be less than 3 or the chi-square for the retrieval state must be less than 5, and aerosol optical thickness (AOT) at 1600 nm must be less than 0.5 (Yoshida et al., 2011). The GOSAT data on 14 February 2010 is released only for RA. The time series of the g-b FTS XCO_2 and XCH_4 are shown in Figs. 7 and 8 with the aircraft and the GOSAT data. The differences of XCO_2 and XCH_4 values from the g-b FTS and GOSAT to those calculated from the aircraft measurements are summarized in Tables 1 to 4. The XCO_2 and XCH_4 values from the aircraft measurements were calculated taking the averaging kernels of the g-b FTS and GOSAT into account. Detailed results on XCO_2 and XCH_4 are described in the next subsections.

5.2 XCO_2

Figure 7 shows the time series of the g-b FTS XCO_2 over Tsukuba along with the aircraft and GOSAT XCO_2 . Retrieved g-b FTS data were filtered using the fractional variation in solar intensity (FVSI) during a measurement measured by a pyranometer. The average values of the g-b FTS during the flight over Tsukuba are indicated at the intermediate times of the flights as shown in Fig. 7. On 20 and 23 February, weather conditions were optimal for direct solar measurement. In contrast, on 14 February, these were not optimal because the sky was partially cloudy. Table 1 summarizes the values of XCO_2 from the aircraft and the g-b FTS and the differences of XCO_2 between the aircraft and the g-b FTS for Tsukuba and Moshiri. The g-b FTS XCO_2 values at Tsukuba are slightly biased low compared to the aircraft XCO_2 values, as listed in

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Table 1. The average difference between the g-b FTS XCO_2 and the aircraft XCO_2 with one standard deviation for the Tsukuba site is 1.32 ± 0.46 ppm, which corresponds to 0.33 ± 0.11 %. This small bias between the Tsukuba g-b FTS and the aircraft XCO_2 remains even after the standard TCCON calibration described in detail in Wunch et al.

(2010) and might be due to the effect of ghosts, artificial spectra that are mirror images of the original spectra, caused by He-Ne laser miss-sampling (Messerschmidt et al., 2010) or of improperly fitting the instrument line shape.

Though the GOSAT SWIR XCO_2 values are relatively low compared with those of the aircraft, as listed in Table 2, this is consistent with the result using GU data reported by Morino et al. (2010) that the GOSAT SWIR XCO_2 is biased low by 8.85 ± 4.75 ppm. The differences at Tsukuba in February 2010 are within the value reported by Morino et al. (2010) except for the value on 14 February, which is released only for RA. On 14 February, thin cirrus clouds were measured at around 11 km using lidar indicating that the retrieved XCO_2 and XCH_4 by GOSAT SWIR data were contaminated by the clouds (Uchino et al., 2011).

At Moshiri, the g-b FTS had a significant low bias and large variance during flight compared with the result obtained over Tsukuba. It is likely that there were clouds in the field of view of the g-b FTS during measurement at Moshiri, but it was difficult to screen retrieved XCO_2 values by the FVSI because the temporal resolution of the pyranometer recorded is 1 min and the scan time for the g-b FTS is less than 1 min. The faster scan speed (20 kHz) of the g-b FTS at Moshiri than the TCCON norm decreased the signal-to-noise ratio of the measured spectra. Currently, the pyranometer measures every 2 s, matching the pyranometer measurement frequency at Tsukuba, and screening by FVSI is possible, so we anticipate a reduction in the uncertainties of XCO_2 and XCH_4 resulting the future.

5.3 XCH_4

The time series of the g-b FTS XCH_4 over Tsukuba are shown in Fig. 8 along with the aircraft and GOSAT values. Table 3 shows the values of XCH_4 measured by the

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aircraft and g-b FTS, and the differences of the g-b FTS data to the aircraft data for Tsukuba and Moshiri. The average difference of the g-b FTS XCH_4 data to the aircraft XCH_4 data is 12.6 ± 5.5 ppb, which corresponds to 0.69 ± 0.29 % over Tsukuba. For XCH_4 , the uncertainty was larger than that of TCCON calibration. This is partly because the compensation by the CH_4 -HF correlation was not carried out as mentioned in Sect. 4. In the TCCON calibration, the average and maximum adjustments by the CH_4 -HF correlation are 0.4 km and 1.8 km in altitude, respectively (Wunch et al., 2010). As a result of the adjustment of CH_4 concentration, the average adjustment of 0.4 km produces a difference within 3 ppb (0.2 %) in the amount of column in our case. Differences from -16 ppb to 13 ppb (from -0.9 % to 0.7 %) appeared in the maximum adjustment of 1.8 km and can partly explain the discrepancy with the TCCON calibration. In this observation, the tropopause height can be determined from meteorological parameters measured by radio sondes. Comparing the differences of the true tropopause heights with those assumed in GFIT algorithm in 14, 20, 23 February, and 26 August are -100 m, 200 m, -500 m, and 200 m, which corresponds to -0.8 , 1.9, -4.4 , and 1.8 ppb, respectively. To compare the aircraft XCH_4 with GOSAT XCH_4 over Tsukuba, as listed in Table 4, the GOSAT data had slightly larger differences compared with the results reported by Morino et al. (2010). The relatively large low bias due to the influence of the cirrus clouds was also seen in XCO_2 on 14 February 2010.

At Moshiri, the difference between the aircraft and the g-b FTS XCH_4 was large compared with the result obtained at Tsukuba because of the same reasons explained for XCO_2 .

6 Conclusions

Aircraft measurements were conducted over Tsukuba and Moshiri for the calibration of the g-b FTSs and the validation of GOSAT. In the February 2010 flights over Tsukuba, we succeeded in performing simultaneous observations of the g-b FTS, the aircraft in situ and flask sampling instruments, and GOSAT.

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Retrieved XCO_2 and XCH_4 values from the g-b FTS measurements show good agreement with the aircraft measurements over Tsukuba. On the contrary, the negative biases in XCO_2 and XCH_4 measured by the g-b FTS were relatively large over Moshiri compared with those over Tsukuba. This was probably due to the lack of screening by the FVSI and the higher scan speed of the g-b FTS.

The GOSAT data underestimate both XCO_2 and XCH_4 compared the aircraft measurements. The average difference of GOSAT SWIR XCO_2 and XCH_4 compared to the aircraft XCO_2 and XCH_4 were 9.08 ± 5.41 ppm ($2.31 \pm 1.37\%$) for XCO_2 and 39 ± 11 ppb ($2.18 \pm 0.64\%$) for XCH_4 excluding the cloudy GOSAT data of 14 February 2010. These average differences are consistent with the preliminary results of GOSAT validation efforts (Morino et al., 2010). The comparisons of the g-b FTS and GOSAT with the aircraft measurement show that the effects of contributing factors such as aerosols and thin cirrus clouds on the retrieval from GOSAT are not negligible. Further validation experiments using instruments with a combination of g-b FTS, aircraft, observation tower, lidar, and skyradiometer are necessary to improve the retrieval algorithm for GOSAT and decrease uncertainties of the GOSAT SWIR XCO_2 and XCH_4 .

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Table 1. XCO_2 obtained from the aircraft and the g-b FTS on each observational day over Tsukuba (14, 20, and 23 February) and Moshiri (26 August 2009). The g-b FTS XCO_2 is the average value during the flight over the observational site. The differences between aircraft XCO_2 and g-b FTS XCO_2 are indicated in the fourth (ppm) and fifth (%) columns. The average difference and its one standard deviation at the Tsukuba site are indicated in fifth row. Note that there is no average and one standard deviation of the difference at the Moshiri site.

Obs. time	Aircraft (ppm)	g-b FTS (ppm)	Difference		Obs. point
			Aircraft-g-b-FTS (ppm)	(Aircraft-g-b-FTS)/Aircraft*100 (%)	
14 Feb 2010	390.70	389.91	0.80	0.20	Tsukuba
20 Feb 2010	391.37	389.87	1.50	0.38	
23 Feb 2010	391.63	389.97	1.66	0.42	
		Avg. diff. (1σ)	1.32 (0.46)	0.33 (0.11)	
26 Aug 2009	381.574	376.851	4.72	1.24	Moshiri

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Table 2. XCO_2 obtained from the aircraft and GOSAT (V01.20) on each observational day over Tsukuba (14, 20, and 23 February). The differences between aircraft XCO_2 and GOSAT SWIR XCO_2 are indicated in the fourth (ppm) and fifth (%) columns. The average difference and its one standard deviation at the Tsukuba site are indicated in fifth row. Note that there is no average and one standard deviation of the difference at the Moshiri site.

Obs. time	aircraft (ppm)	GOSAT (ppm)	difference		Obs. point
			Aircraft-GOSAT (ppm)	(Aircraft-GOSAT)/Aircraft*100 (%)	
14 Feb 2010	391.67	372.42	19.25	4.92	Tsukuba
20 Feb 2010	391.66	386.41	5.25	1.34	
23 Feb 2010	392.33	379.41	12.91	3.29	
		Avg. diff. (1σ)	12.47 (7.01)	3.18 (1.78)	

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Table 3. The same as Table 1, but for XCH_4 .

Obs. time	Aircraft (ppm)	g-b FTS (ppm)	Difference		Obs. point
			Aircraft-g-b-FTS (ppm)	(Aircraft-g-b-FTS)/Aircraft*100 (%)	
14 Feb 2010	1.8023	1.7961	0.0062	0.34	Tsukuba
20 Feb 2010	1.8066	1.7908	0.0158	0.88	
23 Feb 2010	1.8045	1.7887	0.0158	0.88	
		Avg. diff. (1σ)	0.0126 (0.0055)	0.69 (0.29)	
26 Aug 2009	1.7943	1.7565	0.0378	2.11	Moshiri

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Table 4. The same as Table 2, but for XCH_4 .

Obs. time	Aircraft (ppm)	GOSAT (ppm)	difference		Obs. point
			Aircraft-GOSAT (ppm)	(Aircraft-GOSAT)/Aircraft*100 (%)	
14 Feb 2010	1.8122	1.7504	0.0618	3.41	Tsukuba
20 Feb 2010	1.8110	1.7796	0.0313	1.73	
23 Feb 2010	1.8150	1.7671	0.0479	2.64	
		Avg. diff. (1σ)	0.0470 (0.0152)	2.59 (0.84)	

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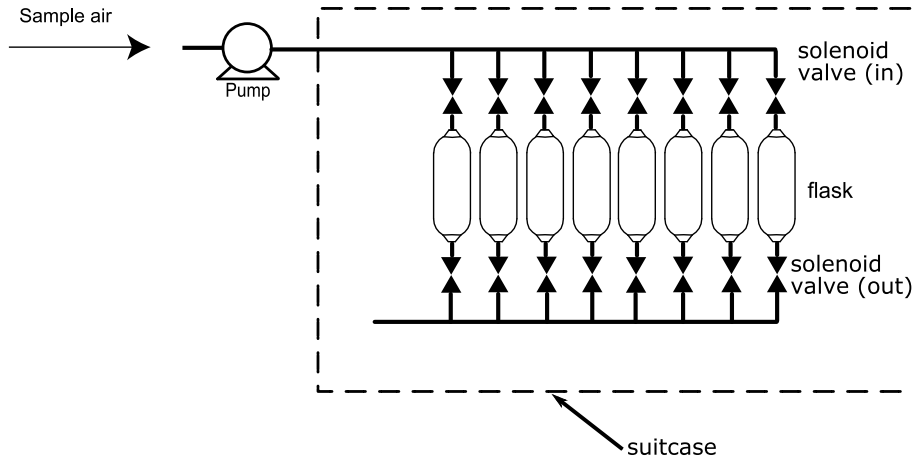
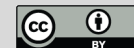


Fig. 1. Schematic diagram of the hand-operated air sampling equipment (HSE). The whole system is in a suitcase equipped with cushioning materials to reduce shocks by airframe vibrations.

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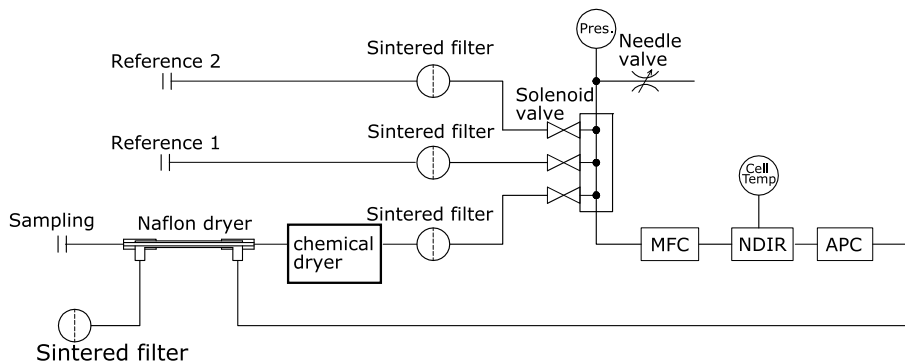


Fig. 2. Schematic diagram of the continuous CO₂ measuring equipment (CME). The flow rate is controlled by a mass flow controller (MFC), and the absolute pressure of the Non-Dispersive InfraRed (NDIR) cell is regulated by an auto pressure controller (APC).

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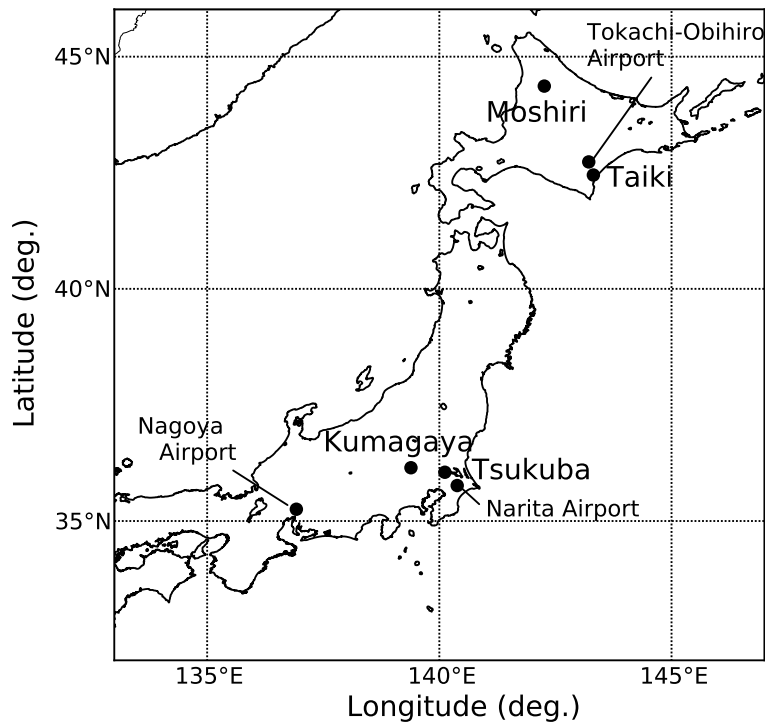


Fig. 3. Observation sites for the present aircraft measurements (Tsukuba, Kumagaya, Moshiri, and Taiki).

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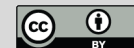
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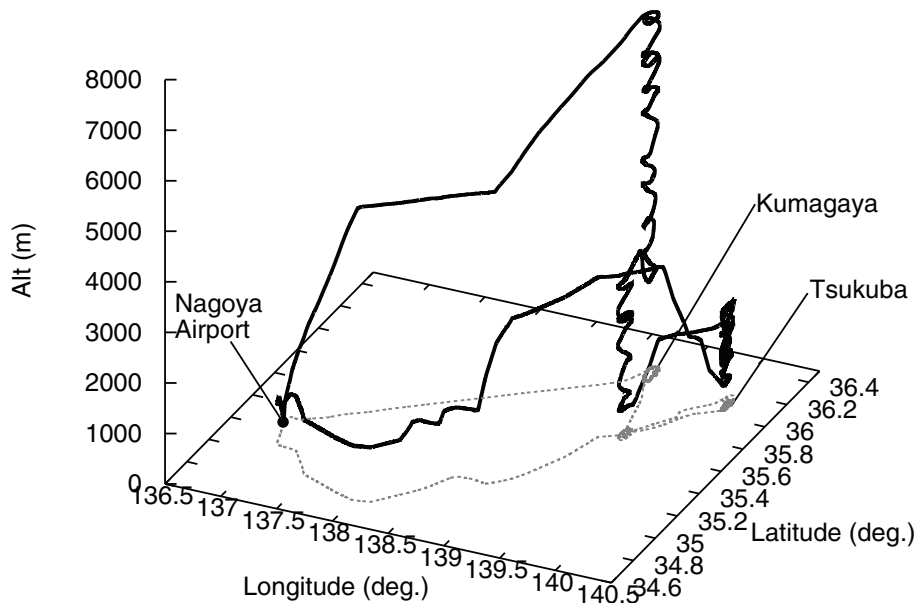


Fig. 4. A flight pattern over Tsukuba performed on 14 February 2010.

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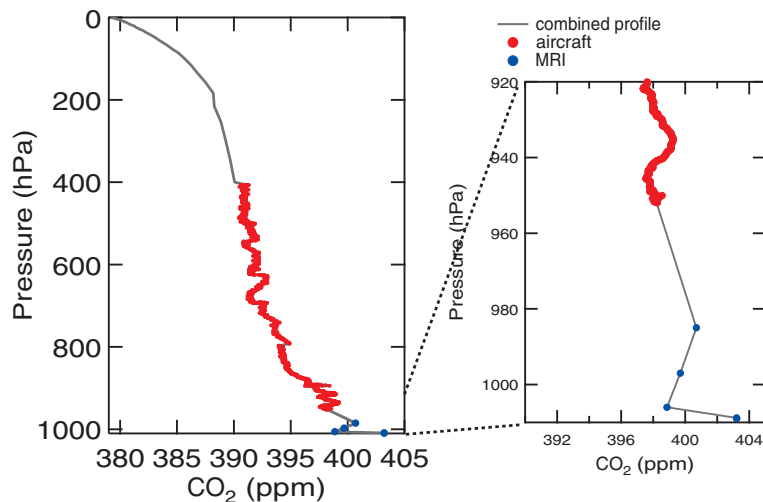


Fig. 5. Combined CO₂ profile observed on 20 February 2010, over Tsukuba and Kumagaya, respectively. Red and blue dots are the aircraft (in situ) data and the meteorological tower data of the Meteorological Research Institute (MRI), respectively. The gray lines show the combined ground, aircraft, and GFIT a priori profiles.

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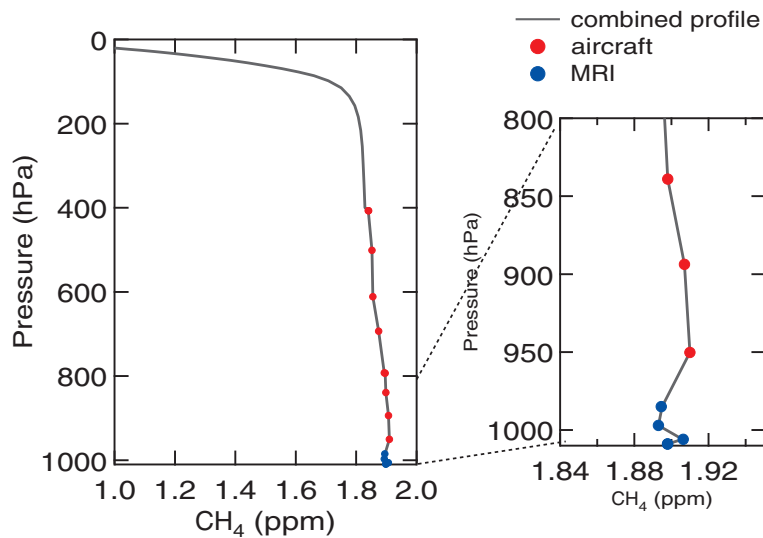


Fig. 6. The same as Fig. 5, but for CH₄. The aircraft data shown are from the flask sampling air.

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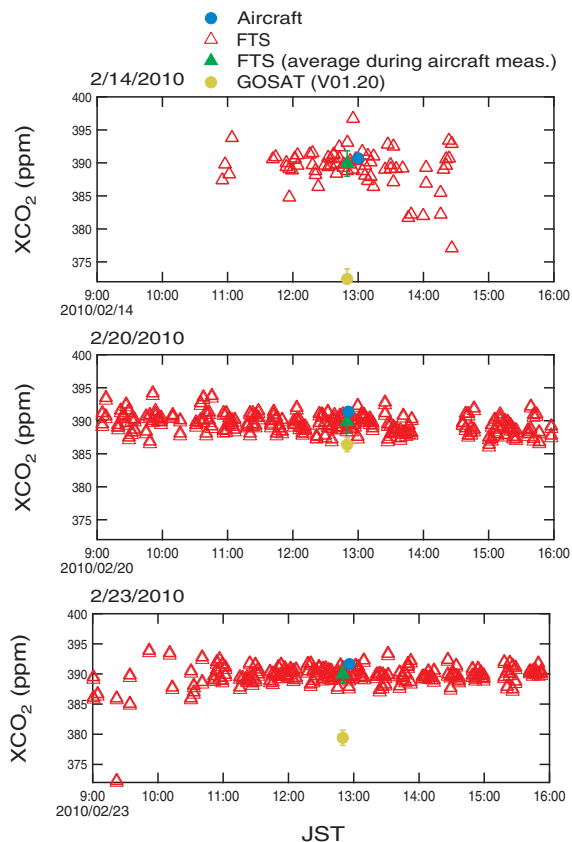
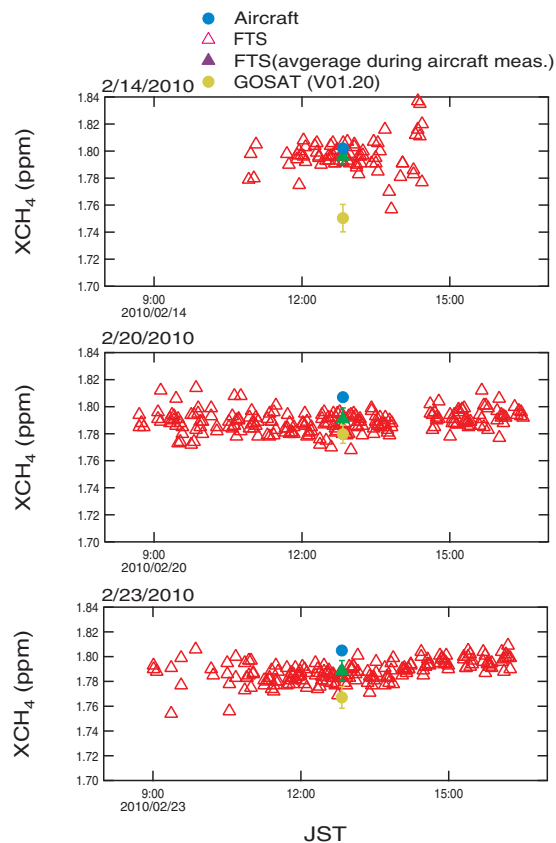


Fig. 7. The time series of the g-b FTS XCO_2 are shown together with the aircraft and the GOSAT SWIR (V01.20) data on each observation day. The GOSAT data on 14 February 2010 is released only for RA. The average values of the g-b FTS during the flight over Tsukuba are indicated at the intermediate flight times.

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**Fig. 8.** The same as Fig. 7, but for XCH_4 .[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)