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CO_2 column-averaged volume mixing ratio derived over Tsukuba from measurements by commercial airlines

M. Araki[1,*], I. Morino[1], T. Machida[1], Y. Sawa[2], H. Matsueda[2], H. Ohyama[3], T. Yokota[1], and O. Uchino[1]

[1]National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[2]Meteorological Research Institute, 1-1 Nagamine, Tsukuba 305-0052, Japan
[3]Japan Aerospace Exploration Agency, Sengen 2-2-1, Tsukuba 305-8505, Japan
[*]now at: Department of Chemistry, Faculty of Science Division I, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan

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Abstract. Column-averaged volume mixing ratios of carbon dioxide (X_{CO_2}) during the period from January 2007 to May 2008 over Tsukuba, Japan, were derived using CO_2 concentrations measured by Continuous CO_2 Measuring Equipment (CME). The CMEs were installed on Japan Airlines Corporation (JAL) commercial airliners, which frequently fly to and from Narita Airport. It was assumed that CO_2 profiles over Tsukuba and Narita are the same. CO_2 profile data for 493 flights on clear-sky days were analyzed in order to calculate X_{CO_2} with one of two ancillary datasets: "Tsukuba observational" data (rawinsonde and meteorological tower), or "global" forecast/reanalysis and climatological data (NCEP and CIRA-86). The amplitude of the seasonal variation of X_{CO_2} using the ancillary data measured in Tsukuba (X_{CO_2}(Tsukuba observational)) was determined by a least squares fit using a harmonic function to roughly evaluate the seasonal variation over Tsukuba. The highest and lowest values of the obtained fitted curve in 2007 for X_{CO_2} (Tsukuba observational) were 386.4 ± 1.0 and 381.7 ± 1.0 ppm in May and September, respectively, where the errors represent 1 standard deviation of the fit residuals. The dependence of X_{CO_2} on the type of ancillary dataset was evaluated. The average difference between X_{CO_2} from global climatological data, X_{CO_2} (global), and X_{CO_2} (Tsukuba observational), i.e., the bias of X_{CO_2} (global) based on X_{CO_2} (Tsukuba observational), was found to be -0.621 ppm with a standard deviation of 0.682 ppm. The uncertainty of X_{CO_2} (global) based on X_{CO_2} (Tsukuba observational) was estimated to be 0.922 ppm. This small uncertainty relative to the GOSAT precision suggests that calculating X_{CO_2} using data from airliners and global climatological data can be applied to the validation of GOSAT products for X_{CO_2} over airports worldwide.

Correspondence to: M. Araki
(araki@rs.kagu.tus.ac.jp)

1 Introduction

Climate change is one of our most important environmental problems. Over the past 200 years, the concentration of atmospheric carbon dioxide (CO_2), a major greenhouse gas, has increased rapidly from about 280 to 380 ppm (IPCC, 2007). This increase in CO_2 concentration enhances radiative forcing of the atmosphere and thus may contribute to climate change. The prediction of future atmospheric CO_2 concentrations and its influence on climate will require accurate quantification of the distribution and variability of CO_2 sources and sinks, which have been derived from atmospheric CO_2 concentration data by using the inversion of atmospheric transport. Atmospheric CO_2 concentrations are measured with high accuracy, with the majority of the measurements being made at ground stations and meteorological towers using flask sampling and/or Non-Dispersive Infra-Red (NDIR) analyzer. However, because of the sparseness of existing ground stations and the limitation of their altitudinal range, present estimates of CO_2 sources and sinks have large uncertainties (Gurney et al., 2002).

Rayner and O'Brien (2001) demonstrated that global space-based observations of monthly mean column-averaged CO_2 volume mixing ratios (VMR; precision $\leq 1\%$), denoted as X_{CO_2}, can be useful for reducing the uncertainties in regional ($8^\circ \times 10^\circ$ footprint) CO_2 source and sink estimates. Global X_{CO_2} values can be derived from space-based nadir-looking observations of sunlight scattered from the earth's surface in the near-infrared spectral region (e.g., Mao and Kawa, 2004).

The Greenhouse gases Observing SATellite "IBUKI" (GOSAT) measures the concentrations of CO_2 and methane (CH_4) from space (Yokota et al., 2004; Hamazaki et al., 2005; Yokota et al., 2009). Global X_{CO_2} and X_{CH_4} products are obtained from the Fourier Transform Spectrometer (FTS) of the Thermal and Near-infrared Sensor for Carbon Observation (TANSO) onboard GOSAT.

Although satellite sensors provide global observations, the data are less accurate than ground-based observations and direct air measurements and need to be validated against more accurate independent datasets. Comparisons of total columns of CO, CH_4, CO_2, and N_2O were carried out between the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) satellite instrument and ground-based FTS data obtained from 11 sites (Dils et al., 2006). Values of X_{CO_2} over Park Falls, Wisconsin, USA, obtained with a ground-based FTS (Bruker IFS 125 HR), were evaluated by an Orbiting Carbon Observatory (OCO) retrieval algorithm and were compared with those obtained with SCIAMACHY (Bösch et al., 2006). The ground-based FTS is a powerful tool for the validation of X_{CO_2} satellite products. A network of ground-based FTSs that record direct solar spectra in the near-infrared spectral region, named Total Carbon Column Observing Network (TCCON, Toon et al., 2009), provides essential validation data for SCIAMACHY and GOSAT. The network consists of 14 sites in Europe, Oceania, North America, and Japan as of March 2010. Additional observation sites for the validation of satellite products are expected, e.g., in tropical zones and South America.

The Comprehensive Observation Network for TRace gases by AIrLiner (CONTRAIL) project (Machida et al., 2008) has been observing vertical CO_2 profiles over 43 airports in the world since 2005. Five Japan Airlines Corporation (JAL) commercial airliners are instrumented with the Continuous CO_2 Measuring Equipment (CME) and most of the flights originate from Narita International Airport (hereafter Narita) in Japan. Vertical CO_2 profiles are obtained during ascents and descents of the airliners. X_{CO_2} values derived from the CONTRAIL profiles can be used to validate the X_{CO_2} data observed by GOSAT. Tsukuba is the primary validation site for GOSAT, and is situated 40 km from Narita. The CONTRAIL project could dramatically increase the number of GOSAT validation sites. To develop a method of calculating X_{CO_2} using CONTRAIL data, this paper will focus on using CONTRAIL profiles over Narita with the extensive meteorological data measured in Tsukuba.

Table 1. Types of analyses of X_{CO_2} for ancillary meteorological and model data.

X_{CO_2}(Type)	Analysis Type[a]		
	X_{CO_2}(I)	X_{CO_2}(I′)	X_{CO_2}(II)
MRI CO_2 [b]	Yes	Yes	No
Number density profile	Sonde	CIRA-86	CIRA-86
NCEP PBL	Yes	Yes	No
Tropopause	Sonde	Sonde	NCEP

[a] Analysis types are defined by the ancillary meteorological data used to calculate X_{CO_2} over Tsukuba. Types I and II analyses use Tsukuba observational data and global climatological data, respectively.
[b] In situ CO_2 tower measurements.

In the present work, values of X_{CO_2} were derived over Tsukuba during the period from January 2007 to May 2008 for which Tsukuba observational data were used to add information at altitudes not measured by the instruments aboard the aircraft. To calculate X_{CO_2} over other airports around the world, global climatological data must be used in addition because there are limited numbers of nearby observations. Thus two types of datasets were alternatively used as ancillary meteorological data to calculate X_{CO_2}: Tsukuba observational data (rawinsonde and a meteorological tower) and global climatological data (National Centers for Environmental Prediction [NCEP] and Committee on Space Research [COSPAR] International Reference Atmosphere [CIRA]-86). The dependence of X_{CO_2} on the type of the dataset was calculated, and the bias and uncertainty of X_{CO_2}(global) based on X_{CO_2}(Tsukuba observational) were estimated. Seasonal variation parameters of X_{CO_2} were obtained by a least squares fit to roughly evaluate the seasonal variation over Tsukuba. In addition, X_{CO_2}(Tsukuba observational) were compared with X_{CO_2} obtained by the ground-based FTS (Ohyama et al., 2009) during the study period.

2 Analysis

On the present work, data from the Continuous CME in CONTRAIL, which have an overall precision of 0.2 ppm (Machida et. al., 2008), were used to form the majority of the CO_2 profiles in calculating X_{CO_2}. The data observed during the ascent and descent of the airliners were taken as vertical CO_2 profiles over Narita. Two types of analyses using either Tsukuba observational data (type I analysis) or global climatological data (type II analysis) as the ancillary meteorological data were performed to calculate X_{CO_2} (namely, X_{CO_2}(I) and X_{CO_2}(II)) over Tsukuba. The types of analyses and their nomenclature are summarized in Table 1.

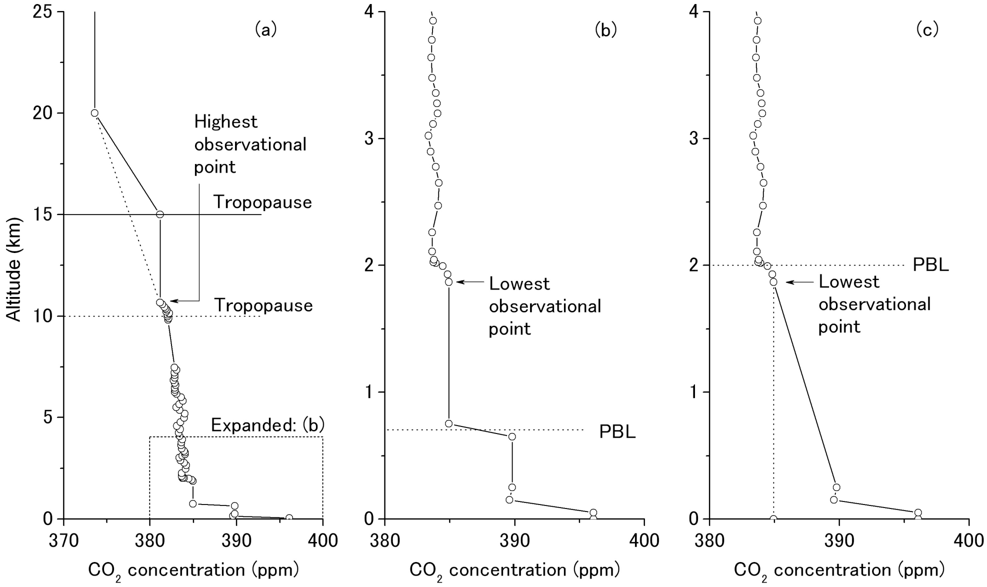

Fig. 1. CO_2-profile assumption over Tsukuba. **(a)** High-altitude profiles: The solid and dotted lines show cases in which the tropopause is higher and lower, respectively, than the highest observational point by an airliner. The rectangular area is expanded in **(b)** and **(c)**. (b) Low-altitude profile: The PBL is lower than the lowest observational point. (c) Low-altitude profiles: the solid line shows a case in which the PBL is higher than the lowest observational point. The dotted line shows an example for which the meteorological-tower datum is missing. All type II analyses use a version of the dotted line in (c) for the low-altitude profile. The type I analysis is the case described in the text.

To obtain X_{CO_2} over Tsukuba, it was assumed that the CO_2 profile over Tsukuba (36.1° N, 140.1° E) is the same as that over Narita (35.8° N, 140.4° E). In addition, assumptions must be made about the CO_2 profiles above and below the altitudes observed by the airliners (from about 0.5–2 km to about 10–11 km). These assumptions are described below.

Measurements have shown that the stratospheric CO_2 concentration is constant above an altitude of about 20 km and lags about five years behind that of the global mean CO_2 concentration in the free troposphere (Aoki et al., 2003). An average of 381.2 ppm in the free troposphere in 2006 with a growth rate of 1.9 ppm/yr (WMO, 2006), for example, yields concentrations of 373.6 and 375.5 ppm in the stratosphere for 2007 and 2008, respectively. When an airliner does not fly above the tropopause, the CO_2 concentration at the highest observational point (altitude) was assumed to be constant up to the tropopause and the profile from the tropopause to 20 km was linearly interpolated with respect to altitude as shown by the solid line in Fig. 1a. When an airliner crosses the tropopause, the profile from the highest observational point to 20 km was assumed to be linear with respect to altitude as shown by a dotted line in Fig. 1a. For a type I analysis, the height of the tropopause was obtained from a rawinsonde observation at the Tateno Aerological Observatory (36.1° N, 140.1° E) of the Japan Meteorological Agency (JMA). The lowest tropopause as identified by the rawinsonde observation was selected from several observed tropopauses, because the lowest tropopause is generally the boundary between the troposphere and the stratosphere. Since the tropopause observations by rawinsondes were made twice a day at 00:00 and 12:00 h UTC, the tropopause height at a given time was determined by linear interpolation. For a type II analysis, the tropopause height was obtained from NCEP's Model Analyses and Forecasts Global Forecast System (GFS), which was usually consistent with the lowest tropopause identified by the rawinsonde observation.

Within the planetary boundary layer (PBL), the CO_2 concentrations observed at a meteorological tower (36.1° N, 140.1° E, Inoue and Matsueda, 1996, 2001) at the Meteorological Research Institute (MRI), Tsukuba, Japan were used in the case of a type I analysis. The CO_2 concentrations were observed at 1.5, 25, 100, and 200 m above the ground with a precision reported to be better than 0.1 ppm using an NDIR analyzer (Inoue and Matsueda, 1996). If the altitude of the lowest observational point of an airliner was higher than that of the PBL, it was assumed that the CO_2 concentration at the lowest observational point (altitude 0.5∼2 km) of an airliner was constant down to the PBL as shown by a solid line in Fig. 1b. If it was lower than the PBL, a linear profile was assumed between the lowest observational point of the airliner and the highest one (200 m) of the meteorological tower as shown by a solid line in Fig. 1c. If the datum from the meteorological tower was missing, the concentration of the lowest observational point of the airliner was extended down to the ground as shown by a dotted line in Fig. 1c (6% of MRI tower data were missing in the present analysis). The PBL height was obtained from NCEP, as systematic determination of the PBL height from rawinsonde data is difficult. The PBL height data from NCEP with a $1^\circ \times 1^\circ$ grid were linearly interpolated with respect to the geographical coordinates of Narita. Analyzed PBL heights were available four times (00:00 h, 06:00 h, 12:00 h, and 18:00 h UTC) daily from NCEP, and forecasted PBL heights were used for the midpoint between the analyses. The PBL data were then linearly interpolated to the takeoff or landing times. In a type II analysis, the concentration at the lowest observational point of an airliner was extended down to the ground irrespective of the PBL height, as shown by a dotted line in Fig. 1c.

Rawinsonde data were utilized for the number density profiles of dry-air in type I analyses. The rawinsonde observations were made twice per day at 00:00 h and 12:00 h UTC. The temporally closest rawinsonde data were used. Because the vertical resolution of rawinsonde observations is a few hundred meters, the number density at a specified altitude was obtained by logarithmic interpolation. Observed total densities of air by the rawinsonde were corrected at each altitude for the water number density using the relative humidity observed by the same rawinsonde. Since rawinsonde data exist up to about 30 km, for altitudes over 30 km, the US standard atmosphere, which is a model that defines values for atmospheric temperature, density, pressure, and other properties over a wide range of altitudes (NOAA, NASA, US Air Force, 1976), was used to generate the number density profile. In type II analyses, CIRA-86 data having monthly mean values in a 5°-latitude grid were employed. CIRA-86 data were linearly interpolated from the 5°-latitude grid to the latitude of Narita. Monthly mean values of CIRA-86 were applied on a monthly basis, without daily interpolation.

To obtain X_{CO_2}, numerical altitudinal integration was executed as a summation of 100-m layers up to an altitude of 85 km. Homogeneously mixed atmosphere was assumed in each layer. Observations by the airliners occurred at intervals of several tens to hundreds of meters. The CO_2 concentration at an altitude of $100 \cdot n + 50$ m ($n = 1, 2, 3\ldots$) was linearly interpolated with the two neighboring observational points and the result was utilized as the concentration of the layer from $100 \cdot n$ to $100 \cdot (n+1)$ meters. As mentioned in regards to Fig. 1b and c, a linear interpolation between the lowest observational point by an airliner and the highest observational point by the meteorological tower was also performed to calculate the concentrations of the layers for the region with missing data, with an altitudinal width of 0.5∼2 km. In the case of the meteorological tower data, the CO_2 concentrations of the lowest three layers were estimated as follows:

$$C_{\text{layer}}(0-100) = 0.5 \cdot C_{\text{tower}}(100) + 0.4 \cdot C_{tower}(25) + 0.1 \cdot C_{\text{tower}}(1.5), \quad (1)$$

$$C_{\text{layer}}(100-200) = 0.5 \cdot C_{\text{tower}}(200) + 0.5 \cdot C_{tower}(100), \quad (2)$$

$$C_{\text{layer}}(200-300) = 1.0 \cdot C_{\text{tower}}(200), \quad (3)$$

where C_{layer} is the CO_2 concentration in the layer and C_{tower} is that observed at the tower. Numbers in parentheses for C_{layer} and C_{tower} indicate the altitudinal regions (in meters) of the layers and observational heights (in meters) in the tower, respectively. The coefficient of each term in equations (1–3) was obtained based on the assumption that the observed concentrations at 200, 100, 25, and 1.5 m in the tower are the averaged concentrations of the layers between 150 and 300, 50 and 150, 10 and 50, and 0 and 10 m, respectively.

A flight was excluded if its minimum altitude was greater than 4 km or the maximum altitude was less than 5 km because of the large altitudinal range with missing data.

In the present work, using CONTRAIL data for January 2007–May 2008 over Narita and based on the above assumptions, data from 493 flights by 5 airliners in clear-sky were analyzed, since only the clear-sky data are suitable for successful GOSAT retrievals. "Clear-sky" conditions were determined by the solar absorption spectra measured by an FTS in Tsukuba (Ohyama et al., 2009). X_{CO_2} from the ground level to an altitude of 85 km, i.e., the entire altitudinal range, and X_{CO_2} for the altitudinal range of 2–10 km (hereafter X'_{CO_2}) were calculated and are shown in Fig. 2. A comparison between X_{CO_2} and X'_{CO_2} can demonstrate the effect of the low-altitude atmosphere on X_{CO_2}.

3 Results and discussion

3.1 Analysis-type dependence for X_{CO_2}: number density of air

To obtain X_{CO_2} over airports worldwide, global data must be utilized for the number density of air. CIRA-86 is one such global dataset. Meteorological data from rawinsonde measurements, which are convertible to number densities of air, were obtained over Tateno in Tsukuba. In the present work, number densities obtained from CIRA-86 were validated with those calculated from the rawinsonde, since an uncertainty in the number densities increases the error on X_{CO_2}. Hereafter, a type I analysis that used CIRA-86 data is referred to as a type I′ analysis (Table 1). The profiles of CIRA-86 number densities are similar to those of the rawinsonde, and the differences (1–2%) between them in the altitude range of 0–10 km could be from daily pressure variability.

The differences between X_{CO_2} by CIRA-86 and by rawinsonde were derived for January 2007–May 2008 (Table 2). The average difference between X_{CO_2}(I′) and X_{CO_2}(I), which is the bias of X_{CO_2}(I′) based on X_{CO_2}(I), was found to be −0.043 ppm with a standard deviation of 0.067 ppm. The uncertainty (=$\{(\text{Bias})^2 + (\text{Standard deviation})^2\}^{1/2}$) of X_{CO_2}(I′) based on X_{CO_2}(I) was 0.080 ppm. These were reduced by half for X'_{CO_2} (Table 2). Because the uncertainties are small, the number densities of CIRA-86 are admissible as global data to derive X_{CO_2}.

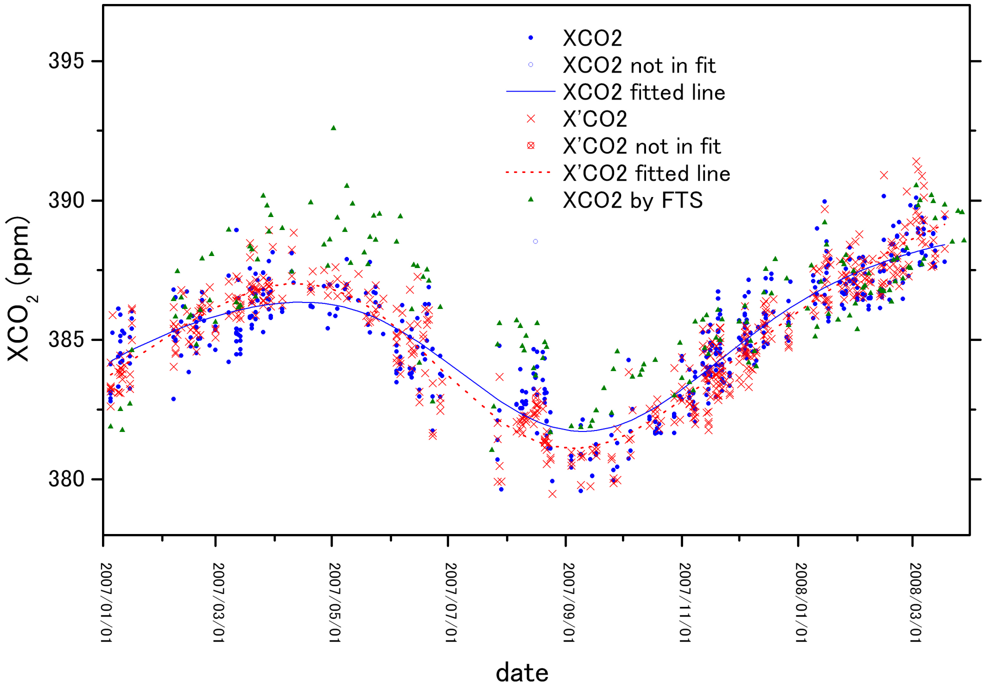

Fig. 2. Time series of X_{CO_2} and X'_{CO_2} from type I analysis over Narita using CONTRAIL data from January 2007 to May 2008. Data from 493 flights by five airliners were analyzed. X_{CO_2} (blue marks and solid blue line) were numerically integrated to cover the entire altitudinal range, i.e., from the ground level to the lower thermosphere (85 km), and for X'_{CO_2} (red marks and dotted red line) over the altitudinal range of 2–10 km. Data on 16 August 2007 were not included in the fit. Daily averaged X_{CO_2} using the scaling retrieval algorithm by FTS are plotted by green marks.

Table 2. Relative uncertainties of X_{CO_2} based on type I analysis (ppm)[a]. To show small relative values, the uncertainties are given to 3 decimal places.

Altitudinal range			Analysis Type			
			X_{CO_2}(I)	X_{CO_2}(I′)	X_{CO_2}(II)	X_{CO_2}(II–I′)
X_{CO_2}	Entire	Bias	0.0	−0.043	−0.621	−0.578
		Standard deviation	0.0	0.067	0.682	0.691
		Uncertainty[b]	0.0	0.080	0.922	0.901
X'_{CO_2}	2–10 km	Bias	0.0	−0.018	−0.019	−0.001
		Standard deviation	0.0	0.029	0.037	0.022
		Uncertainty[b]	0.0	0.034	0.041	0.022

[a] We assumed that the type I analysis defines the real X_{CO_2} in the present analysis.
[b] (Uncertainty) = $\{(\text{Bias})^2 + (\text{Standard deviation})^2\}^{1/2}$

3.2 Analysis-type dependence for X_{CO_2}: Tsukuba observational data and global data

CO_2 ground concentration data are often difficult to obtain for airports worldwide. Therefore the type II analysis does not use the CO_2 ground concentration and assumes that the CO_2 profile is uniform through the PBL, i.e., that there is less influence, compared to the type I analysis, of an air parcel that includes a high concentration CO_2 from a metropolis and/or a local CO_2 source.

During the period between January 2007 and May 2008, the differences between X_{CO_2}(I) and X_{CO_2}(II) were derived. The average difference, which is the bias of X_{CO_2}(II) against X_{CO_2}(I), was found to be −0.621 ppm with a standard deviation of 0.682 ppm. The uncertainty of X_{CO_2}(II) based on X_{CO_2}(I) was 0.922 ppm. In many cases, the observed CO_2 ground concentration was higher than that at the lowest aircraft altitude, which is likely the reason for the bias.

X'_{CO_2} shows remarkably reduced uncertainties (Table 2), which may indicate small effects caused by CO_2-profile turbulence around the PBL and small influences by air parcels that include high-concentration CO_2 from the Tokyo metropolitan area and a local CO_2 source. Furthermore, $X_{CO_2}(I')$ were compared with $X_{CO_2}(II)$ in order to subtract the dependence on air particle number-density datasets from the uncertainty of $X_{CO_2}(II)$ based on $X_{CO_2}(I)$. The differences between $X_{CO_2}(I')$ and $X_{CO_2}(II)$ were obtained. The average of the differences, which is the bias of $X_{CO_2}(II)$ against $X_{CO_2}(I')$, was found to be −0.578 ppm with a standard deviation of 0.691 ppm. The uncertainty of $X_{CO_2}(II)$ based on $X_{CO_2}(I')$ was 0.901 ppm. Although the dependence on the number-density datasets was subtracted, the decrease in the uncertainty of $X_{CO_2}(II)$ was small. Thus the uncertainty of $X_{CO_2}(II)$ strongly depends on the profile assumption around the PBL, as Narita and Tsukuba may have inflows of air parcels over the Tokyo metropolitan area and over a local CO_2 source that disturbs the CO_2 profile uniformity around the PBL. In an analysis at another airport that has a uniform CO_2 profile around the PBL, the uncertainty of X_{CO_2} will be better than that over Tsukuba.

3.3 Variability of X_{CO_2} within 6 h around 13:00 h local time (LT): suitability for GOSAT validation

The variability of X_{CO_2} in a limited time window must be clarified, since regular observations by GOSAT need to be validated by using non-regular observations by the airliners. We focused on a set of profiles in a 6-h window centered on the GOSAT overpass time (around 13:00 h LT). The standard deviations of X_{CO_2} by type I analyses for windows containing more than 3 flights were determined for the January 2007–May 2008 period. The standard deviations of X_{CO_2} that were obtained for 14 windows were averaged. Variabilities – the averages of the standard deviations – were found to be 0.52 and 0.42 ppm for X_{CO_2} and X'_{CO_2}, respectively. A limited altitudinal range (2–10 km in X'_{CO_2}) did not yield a noticeable decrease in variability compared with the full altitudinal range (X_{CO_2}). The variabilities originated mainly from the variability of the CO_2 profiles observed by airliners. However the variabilities are within the allowance of 1% for GOSAT data retrieval (Yokota et al., 2004). The majority of the uncertainties of X_{CO_2}(I′ and II) based on the real X_{CO_2} can be derived from the difference between the real profiles and the assumed high- and low-altitude profiles and are difficult to estimate. We discuss the uncertainties of X_{CO_2}(II and I′) based on $X_{CO_2}(I)$ in Sects. 3.1 and 3.2. For the validation of GOSAT data, the variability of $X_{CO_2}(I)$ within 6 h discussed in this section may be one of the most effective uncertainties of $X_{CO_2}(I)$ based on the real X_{CO_2}.

3.4 Amplitude of seasonal variation

In order to determine the seasonal variation parameters, the $X_{CO_2}(I)$ data obtained by each flight were fitted to the following function (Matsueda et al., 2008; Thoning et al., 1989):

$$f(t) = a_1 + a_2 \cdot t + a_3 \cdot t^2 + a_4 \cdot \sin(2\pi t) + a_5 \cdot \cos(2\pi t) + a_6 \cdot \sin(4\pi t) + a_7 \cdot \cos(4\pi t), \quad (4)$$

where t is a variable of time in the unit of years from the starting date of the computation on 1 January 2003. Coefficient a_1 is the trend of X_{CO_2} on the starting date; a_2 and a_3 indicate the growth rate and its second order, respectively; a_4 and a_5 describe the first harmonic, i.e., the seasonal cycle; and a_6 and a_7 describe the second harmonic. Since the obtained X_{CO_2} data in the present work were limited to 15 months, the value of a_3 was fixed at 0.0. The values of a_1, a_2, a_4, a_5, a_6, and a_7 were determined by a least-squares fit. Although Matsueda et al. used the third harmonic, the large variability of X_{CO_2} in the present work can interfere with the determination of the third harmonic.

Abnormally high concentrations of X_{CO_2} – several ppm higher than regular data – were measured for a number of flights in August 2007. These may have been caused by inflows of air parcels from over the Tokyo metropolitan area to over Narita or Tsukuba. Flights from and to Narita can be classified into those that take off or land in the northern airspace of the airport, and those that take off or land in the southern airspace. The observational points below an altitude of 1 km were 20–30 km from Tsukuba for flights landing and taking off to the north, and 50–60 km from Tsukuba for those in the south. The high concentrations of X_{CO_2} of more than 382.5 ppm recorded in August 2007 were almost always from flights that take off or land in the southern airspace. CO_2 profiles with a high concentration of X_{CO_2} show high concentrations of CO_2 in the low altitudinal region (0–2 km). If the concentration of CO_2 observed in the low altitudinal region by an aircraft that takes off or lands in the southern airspace is higher than that in the MRI tower and is $>$400 ppm, the implication is that air parcels over the Tokyo metropolitan area that have a high concentration of CO_2 have not reached Tsukuba; thus the assumption of uniformity of the CO_2 profile over Tsukuba and Narita is incorrect. A CO_2 profile with this condition cannot be used for GOSAT data validation. In the present work, only one flight on 16 August 2007 that had a value of X_{CO_2} of 388.5 ppm had this condition (shown in Fig. 3) and the value of X_{CO_2} was not included in the fit.

The standard deviation of the differences between X_{CO_2} and the fitted curve was 0.98 ppm (0.74 ppm for X'_{CO_2}). The obtained coefficients are listed in Table 3 and the fitted curves of X_{CO_2} and X'_{CO_2} are shown in Fig. 2. Generally in the Northern Hemisphere, plant activity causes the lowest value of X_{CO_2} to occur around September and the highest around March and April. The timing of the lowest value arises from CO_2 absorption by plant photosynthesis that is sufficiently

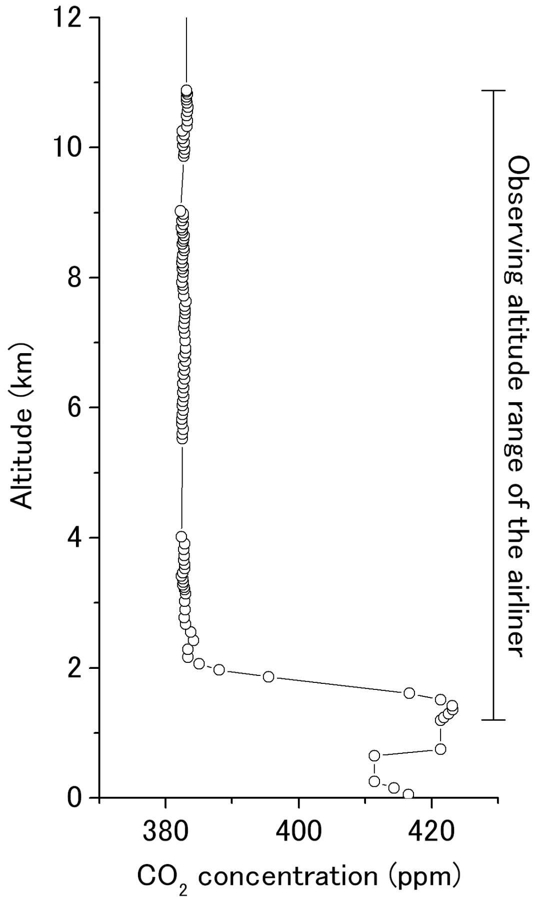

Fig. 3. An example of a profile of an inflowing air parcel from over the Tokyo metropolitan area to over Narita on 16 August 2007.

larger than CO_2 production by plant respiration, whereas the photosynthetic absorption of CO_2 is less in winter, leading to the highest value. The highest and lowest values of the fitted curve in 2007 were 386.4 ± 1.0 and 381.7 ± 1.0 ppm, respectively, for X_{CO_2} and 387.0 ± 0.8 and 381.1 ± 0.8 ppm for X'_{CO_2} in May and September, respectively, where the errors are 1 standard deviation of the residuals in the fit. The amplitude of the tentative seasonal variation, i.e., the peak-to-peak seasonal amplitude, for the 15 months analyzed here was found to be 4.63 ± 0.15 and 5.91 ± 0.13 ppm by the fitted curves for X_{CO_2} and X'_{CO_2}, respectively, where the errors are twice the standard deviation of a_4 in the fit.

The values determined for a_2 (2.27 ± 0.14 and 2.45 ± 0.12 ppm/yr, where the errors are 1 standard deviation of a_2 in the fit) show tentative growth rates for X_{CO_2} and X'_{CO_2} over Tsukuba during the period from January 2007 to March 2008 that are quite similar to the value of 2.2 ppm/yr for the FTS measurements by Ohyama et al. (2009). Our values agree with the values of other measurements such as the ground-based FTS observation at Park Falls (Wisconsin, USA) from 2004 to 2006 (2 ppm/yr, Yang et al., 2007; Washenfelder et al., 2006) and the SCIAMACHY observations at northern low- and mid-latitudes from 2003 to 2006 (1–3 ppm/yr, Buchwitz et al., 2007), although the observational period of the present study is more recent.

Table 3. Coefficients obtained for least-squares fits with Eq. (4) to X_{CO_2} over Tsukuba during the period January 2007–May 2008.

Coefficient[a]	Unit	Entire range[b]	2–10 km
a_1	ppm	374.1929	373.1888
a_2	ppm/yr	2.2672[c]	2.4515[c]
a_3	ppm/yr^2	0.0	0.0
a_4	ppm	2.7184	3.3140
a_5	ppm	0.5133	0.5376
a_6	ppm	−0.3059	−0.4371
a_7	ppm	0.2523	−0.0222

[a] Coefficients in Eq. (4). The coefficient a_3 was fixed at 0.0. See text for details.
[b] Entire altitudinal range, i.e., from the ground level to the lower thermosphere (85 km).
[c] One standard deviation of a_2 is 0.1351 for "Entire range" and 0.1175 for "2–10 km".

3.5 Comparison with X_{CO_2} by FTS

X_{CO_2}(I) determined by the present method and X_{CO_2} by FTS (Bruker IFS 120 HR) were compared for the period from January 2007 to May 2008. Ohyama et al. (2009) retrieved CO_2 volume mixing ratios from solar absorption spectra in the 1.6-µm band measured with the ground-based high-resolution FTS at Tsukuba using profile retrieval and scaling retrieval algorithms. They derived the time series of X_{CO_2} from December 2001 to December 2007. In the present work, we extended the same analysis using the scaling retrieval algorithm to March 2008. Data on partly cloudy days were excluded by the same screening processes of Ohyama et al. (2009). Daily averaged X_{CO_2} by FTS are plotted in Fig. 2 and agree well with the present method in the autumn and winter seasons.

The peak-to-peak seasonal amplitude for X_{CO_2} using FTS measurements over Tsukuba between December 2001 and December 2007 was reported to be about 8 ppm by Ohyama et al. (2009). This peak-to-peak seasonal amplitude is larger than those from the present study reported in Sect. 3.4. Although the general features of the seasonal variations for the FTS measurements shown in Fig. 11 of Ohyama et al. (2009) and the present ones are similar, it would be necessary to extend the observational period before discussing differences in seasonal variations, as the observational period in the present study is much shorter than that in Ohyama et al. (2009).

4 Conclusions

Column-averaged volume mixing ratios of CO_2 (X_{CO_2}) from January 2007 to May 2008 over Tsukuba were derived by using CO_2 profiles measured by CONTRAIL. CO_2 profiles from 493 flights on clear-sky days were analyzed. To calculate X_{CO_2}, two types of datasets, Tsukuba observational data (I) and global data (II), were alternatively used as ancillary data, and X_{CO_2}(II) with global data were compared with the Tsukuba observational data based on X_{CO_2}(I). The bias of X_{CO_2}(II) based on X_{CO_2}(I) over Tsukuba was derived to be -0.621 ppm with a standard deviation of 0.682 ppm. The uncertainty of X_{CO_2}(II) based on X_{CO_2}(I) was estimated to be 0.922 ppm, which is less than 0.3% of X_{CO_2}. The small uncertainty suggests that the present method of X_{CO_2} calculation using CONTRAIL data and the global data can be applied to airports worldwide. Therefore the number of validation sites of GOSAT for X_{CO_2} can be increased.

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