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Makoto Inoue, Isamu Morino, Osamu Uchino, Takahiro Nakatsuru, Yukio Yoshida, et al.. Bias corrections of GOSAT SWIR XCO₂ and XCH₄ with TCCON data and their evaluation using aircraft measurement data. *Atmospheric Measurement Techniques*, 2016, 9, pp.3491-3512. 10.5194/amt-9-3491-2016 . insu-03727107

HAL Id: insu-03727107

<https://insu.hal.science/insu-03727107>

Submitted on 20 Jul 2022

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Bias corrections of GOSAT SWIR XCO₂ and XCH₄ with TCCON data and their evaluation using aircraft measurement data

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Received: 25 November 2015 – Published in Atmos. Meas. Tech. Discuss.: 18 January 2016

Revised: 24 June 2016 – Accepted: 29 June 2016 – Published: 1 August 2016

Abstract. We describe a method for removing systematic biases of column-averaged dry air mole fractions of CO₂ (XCO₂) and CH₄ (XCH₄) derived from short-wavelength infrared (SWIR) spectra of the Greenhouse gases Observing SATellite (GOSAT). We conduct correlation analyses between the GOSAT biases and simultaneously retrieved auxiliary parameters. We use these correlations to bias correct the GOSAT data, removing these spurious correlations. Data from the Total Carbon Column Observing Network (TCCON) were used as reference values for this regression analysis. To evaluate the effectiveness of this correction method, the uncorrected/corrected GOSAT data were compared to independent XCO₂ and XCH₄ data derived from aircraft measurements taken for the Comprehensive Observation Network for TRace gases by AirLiner (CONTRAIL) project, the National Oceanic and Atmospheric Administration (NOAA), the US Department of Energy (DOE), the National Institute for Environmental Studies (NIES), the Japan Meteorological Agency (JMA), the HIAPER Pole-to-Pole observations (HIPPO) program, and the GOSAT validation aircraft observation campaign over Japan. These comparisons demonstrate that the empirically derived bias correction improves the agreement between GOSAT XCO₂/XCH₄ and the aircraft data. Finally, we present spatial distributions and temporal variations of the derived GOSAT biases.

1 Introduction

Atmospheric carbon dioxide (CO₂) and methane (CH₄) are crucially important anthropogenic greenhouse gases that contribute to global warming and future climate change. The Greenhouse gases Observing SATellite (GOSAT), launched in January 2009, is the world's first satellite specialized for measuring the concentrations of atmospheric CO₂ and CH₄ from space (Yokota et al., 2009). Column-averaged dry air mole fractions of CO₂ (XCO₂) and CH₄ (XCH₄) are retrieved from the Short-Wavelength InfraRed (SWIR) spectra of the Thermal And Near-infrared Sensor for carbon Observation – Fourier Transform Spectrometer (TANSO-FTS) onboard GOSAT. Validation of XCO₂ and XCH₄ derived from the GOSAT TANSO-FTS has been conducted by using ground-based high-resolution Fourier Transform Spectrometer (ground-based FTS) data and aircraft measurements (Morino et al., 2011; Saitoh et al., 2012; Yoshida et al., 2013; Inoue et al., 2013, 2014; Gavrillov et al., 2014). The results showed that the GOSAT SWIR XCO₂ measurements (Ver. 02.00) are biased $-1-2$ ppm ($\pm 1-3$ ppm) against the aircraft measurement data (Inoue et al., 2013), whereas GOSAT SWIR XCH₄ measurements (Ver. 02.00) are biased positively by $2-7$ ppb with a standard deviation of about 15 ppb (Inoue et al., 2014).

The systematic biases of the GOSAT XCO₂ and XCH₄ retrievals are produced by many factors including aerosol

optical depth, thin cirrus clouds, and surface pressure retrieval error (e.g., Uchino et al., 2012; Yoshida et al., 2013). These biases can lead to large errors in the estimations of regional fluxes of CO₂ and CH₄ from inversion analyses (Takagi et al., 2011; Maksyutov et al., 2013; Deng et al., 2014; Ishizawa et al., 2016b). Consequently, several studies have described bias corrections of the satellite retrieval data by using linear regression (e.g., Wunch et al., 2011b; Cogan et al., 2012; Guerlet et al., 2013; Schneising et al., 2013; Nguyen et al., 2014). Wunch et al. (2011b) have attempted to correct spatially and temporally varying biases in the Atmospheric CO₂ Observations from Space retrievals of the GOSAT (ACOS-GOSAT; O'Dell et al., 2012; Crisp et al., 2012) data obtained over land using an empirical linear regression model with which they correlated variabilities in XCO₂ retrievals with surface albedo, the difference between the retrieved and a priori surface pressure, airmass, and the oxygen A-band spectral radiance. They used the GOSAT data in the Southern Hemisphere as the reference values for the linear regression and evaluated the bias correction against the Total Carbon Column Observing Network (TCCON) data from the Northern Hemisphere. Following Wunch et al. (2011b), Cogan et al. (2012) performed bias correction of GOSAT XCO₂ data retrieved from the University of Leicester full physics (UoL-FP) retrieval algorithm using pseudo observations based on GEOS-Chem model calculations. Guerlet et al. (2013) used XCO₂ measurements from 12 TCCON sites around the world as a reference for correction of GOSAT XCO₂ data retrieved from the Netherlands Institute for Space Research/Karlsruhe Institute of Technology (SRON/KIT) full physics retrieval algorithm.

In this study, we develop a method for correcting the systematic biases of the GOSAT XCO₂ and XCH₄ retrievals (Ver. 02.21) provided by the National Institute for Environmental Studies (NIES-GOSAT; Yoshida et al., 2013). Similar to Guerlet et al. (2013), we explicitly use TCCON data from 22 sites throughout the world as reference values for the regression analysis. The regression variables and coefficients for correction of GOSAT data are determined separately for observations made over land and those made over the ocean, and we perform this analysis for both XCO₂ and XCH₄. Such a partitioning is sensible because in the SWIR XCO₂ and XCH₄ retrievals, the handling of the surface reflectance is different over land and ocean. In addition, the atmosphere over ocean is generally cleaner than that over land because of the absence of polluted air and aerosols from urban areas. These differences suggest that the bias characteristics of XCO₂ and XCH₄ retrieved over ocean differ from those over land.

This paper is structured as follows. Section 2 presents a brief note on the data sets used and analysis procedure. In Sect. 3, we show a detailed method for correcting GOSAT data and the results of the empirical correction. Our findings and conclusions are given in Sect. 4.

2 Data and analysis methods

2.1 XCO₂ and XCH₄ retrieved from GOSAT TANSO-FTS SWIR spectra

To monitor the spatial distribution of atmospheric greenhouse gases from space, GOSAT was launched on 23 January 2009 into a sun-synchronous orbit with an overpass time of roughly 13:00 local time (Kuze et al., 2009). Over a 3-day period, TANSO-FTS onboard GOSAT makes observations above several tens of thousands of ground points spread over the earth's surface. Measurements in the SWIR and thermal infrared (TIR) bands of TANSO-FTS allow the retrievals over cloud-free regions of XCO₂ and XCH₄, and CO₂ and CH₄ profiles, respectively. (Yoshida et al., 2011, 2013; Saitoh et al., 2012). More recently, Kuze et al. (2016) reported update on the performance of GOSAT TANSO-FTS sensor and important changes to the data product which has been made available to users. In this study, we used Ver. 02.21 XCO₂ and XCH₄ data (Yoshida et al., 2013), which cover the period from April 2009 to May 2014.

2.2 TCCON data

The Total Carbon Column Observing Network (TCCON) is a worldwide network of ground-based FTSS that provide time series of column-averaged abundances of various atmospheric constituents. These constituents, which include CO₂ and CH₄, are retrieved from near-infrared solar absorption spectra using a nonlinear least-squares fitting algorithm referred to as GFIT (Wunch et al., 2010, 2011a). The TCCON data have been used to compare with satellite data and model simulations (Dils et al., 2006; Morino et al., 2011; Schneising et al., 2012; Saito et al., 2012; Heymann et al., 2012; Oshchepkov et al., 2013; Yoshida et al., 2013; Belikov et al., 2013; Dils et al., 2014; Nguyen et al., 2014; Scheepmaker et al., 2015) and elucidate the temporal behavior of greenhouse gases (Wunch et al., 2009; Deutscher et al., 2010, 2014; Messerschmidt et al., 2010; Ishizawa et al., 2016a). In this study, we used TCCON data analyzed with the GGG2014 version of the standard TCCON retrieval algorithm (Wunch et al., 2015) for correction of GOSAT data. The TCCON data are available from the Carbon Dioxide Information Analysis Center (CDIAC) at <http://tcccon.ornl.gov>. The distribution and basic information of 23 TCCON sites used for correction or validation analyses of GOSAT data are shown in Fig. 1a and Table 1, respectively. See Table 1 for the data reference in respective TCCON sites. The TCCON sites are distributed throughout the world including North America, Europe, Asia, and Oceania (Fig. 1a). Due to the absence of coincidence with GOSAT data at Ny-Ålesund, these TCCON XCO₂ and XCH₄ data were not used for correction of GOSAT data; they were, however, used for the analysis of latitudinal distributions described in Sect. 3.3.

2.3 Aircraft-based data

In order to test for remaining biases in the GOSAT data after applying the empirical correction developed using TCCON data, we use aircraft profile data provided by the Comprehensive Observation Network for TRace gases by AirLiner (CONTRAIL) project (Machida et al., 2008), the NOAA Earth System Research Laboratory/Global Monitoring Division (ESRL/GMD; Xiong et al., 2008; Sweeney et al., 2015), the US Department of Energy (DOE; Biraud et al., 2013; Schmid et al., 2014), the National Institute for Environmental Studies (NIES; Machida et al., 2001), the Japan Meteorological Agency (JMA; Tsuboi et al., 2013), the HIAPER Pole-to-Pole Observations (HIPPO) project (Wofsy et al., 2011, 2012; Kort et al., 2012; Santoni et al., 2014), and an aircraft measurement campaign by NIES and the Japan Aerospace Exploration Agency (JAXA) (Tanaka et al., 2012). To calculate aircraft-based XCO₂ and XCH₄ (as described in the next paragraph), we also used tower data from the Meteorological Research Institute (MRI) in Tsukuba (Inoue and Matsueda, 1996, 2001) and the NOAA ESRL/GMD tall tower network in Park Falls, WI and West Branch, IA (Andrews et al., 2014). Details of the aircraft and tower measurements are described in Inoue et al. (2013) and Inoue et al. (2014), except for the JMA aircraft and ground-based measurements. The JMA aircraft measurements are conducted by utilizing the cargo aircraft C-130H of the Japan Ministry of Defense (MOD) to collect flask air samples once a month during a regular flight between the mainland of Japan and Minamitorishima, an island located nearly 2000 km southeast of Tokyo (Tsuboi et al., 2013). In addition, the JMA routinely obtains ground-based measurements at a height of 20 m over Minamitorishima. We used CO₂ and CH₄ profiles from around Minamitorishima derived from aircraft and ground-based data available via the World Data Centre for Greenhouse Gases (WDCGG) website (<http://ds.data.jma.go.jp/gmd/wdogg/>). The typical JMA aircraft sampling altitudes were 0.5–6.5 km. Figure 1b and Table 2 show a global map and basic information, respectively, on every aircraft measurement site used in this study.

Aircraft-based XCO₂ and XCH₄ are calculated by applying the GOSAT SWIR column averaging kernels (CAK) by using the methods developed by Miyamoto et al. (2013) and Inoue et al. (2014), respectively. There is one difference in the aircraft XCH₄ calculation: Inoue et al. (2014) used fixed monthly climatologies for the CH₄ profiles above the tropopause and did not include the yearly trend in CH₄ concentration because of their short analysis period (June 2009 to July 2010). In this study, the yearly trend is explicitly taken into account. According to recent reports from the World Meteorological Organization (WMO), global CH₄ abundance increased from 1789 ppb in 2007 to a high of 1824 ppb in 2013 (WMO, 2008, 2014) with a growth rate of about 6 ppb yr⁻¹. Here, we included this mean annual trend

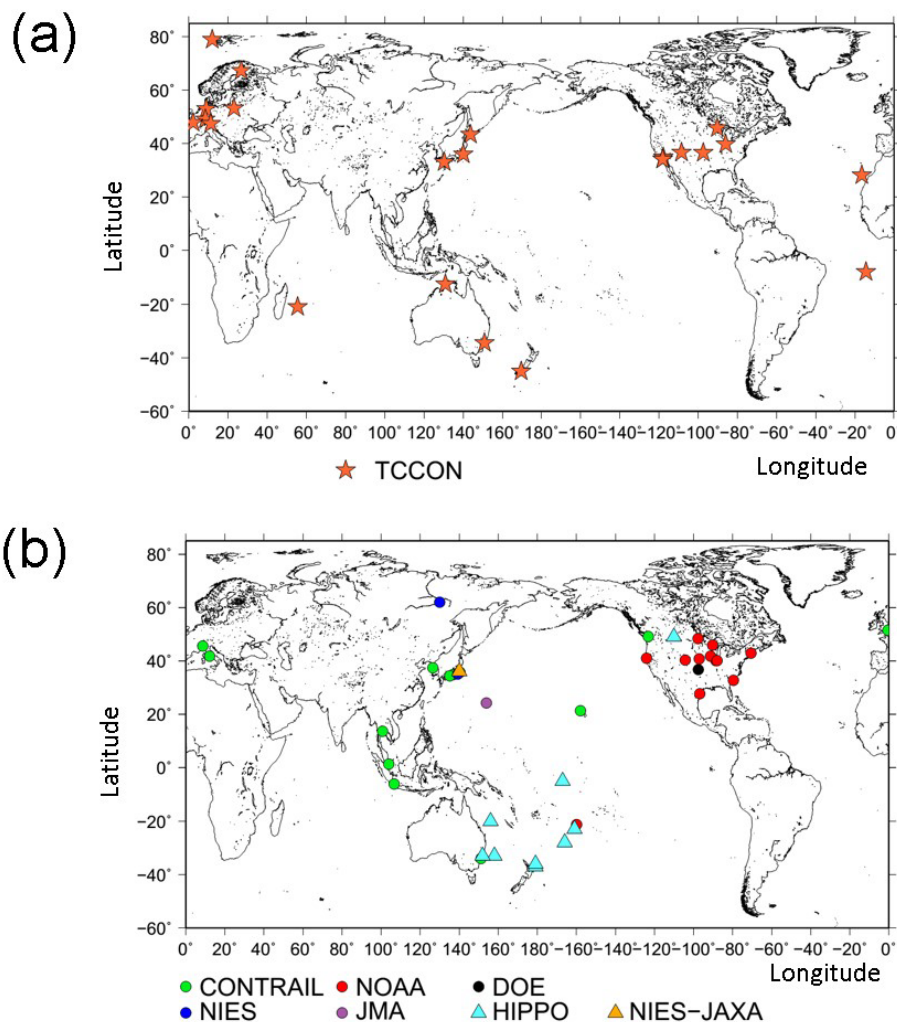


Figure 1. Global distributions of (a) the TCCON sites used for correction and validation of GOSAT data and (b) the aircraft observation sites used for validation of GOSAT data.

(6 ppb yr⁻¹) of CH₄ profiles above the tropopause for the calculation of aircraft-based XCH₄.

2.4 Correction and validation procedure of GOSAT data

Our aim in this study is to correct GOSAT SWIR XCO₂ and XCH₄ (Ver. 02.21) by multiple linear regression using TCCON data as reference values. In Sect. 3.1, we explain the details of the empirical correction method. To evaluate the effectiveness of this correction method, we compare uncorrected/corrected GOSAT XCO₂ (XCH₄) to independent aircraft-based XCO₂ (XCH₄) based on aircraft measurements by CONTRAIL, NOAA, DOE, NIES, JMA, the HIPPO project, and the NIES-JAXA joint campaign (Sect. 3.2). We compare GOSAT data retrieved on the same day and within $\pm 5^\circ$ latitude/longitude boxes centered on each aircraft profile. We also investigate the spatial distribu-

tions of uncorrected/corrected GOSAT data (Sect. 3.3), and the temporal behavior of the GOSAT XCO₂ and XCH₄ biases (Sect. 3.4).

3 Results and discussion

3.1 Parameter dependency of GOSAT biases and multiple linear regression for correction of GOSAT data

The bias correction of GOSAT XCO₂ and XCH₄ (Ver. 02.21) uses multiple linear regression. Before formulating the regression equations, we perform a correlation analysis between the GOSAT biases and simultaneously retrieved auxiliary parameters at TCCON sites. Here, the differences between GOSAT XCO₂ (XCH₄) and TCCON XCO₂ (XCH₄) are referred to as Δ XCO₂ (Δ XCH₄). Figures 2a–d and 3a show several examples of scatter diagrams between Δ XCO₂

Table 1. Basic information on the TCCON sites used for correction and validation of the GOSAT data.

Site	Latitude (deg. N)	Longitude (deg. E)	Elevation (m)	Region	Data reference (DOI number)
Ny-Ålesund	78.90	11.90	20	Spitzbergen, Norway	doi:10.14291/tcon.ggg2014.nyalesund01.R0/1149278
Sodankylä	67.37	26.63	188	Finland	doi:10.14291/tcon.ggg2014.sodankyla01.R0/1149280
Białystok	53.23	23.03	180	Poland	doi:10.14291/tcon.ggg2014.bialystok01.R1/1183984
Bremen	53.10	8.85	27	Germany	doi:10.14291/tcon.ggg2014.bremen01.R0/1149275
Karlsruhe	49.10	8.44	120	Germany	doi:10.14291/tcon.ggg2014.karlsruhe01.R1/1182416
Orléans	47.97	2.11	130	France	doi:10.14291/tcon.ggg2014.orleans01.R0/1149276
Garmisch	47.48	11.06	740	Germany	doi:10.14291/tcon.ggg2014.garmisch01.R0/1149299
Park Falls	45.95	−90.27	472	USA	doi:10.14291/tcon.ggg2014.parkfalls01.R0/1149161
Rikubetsu	43.46	143.77	361	Japan	doi:10.14291/tcon.ggg2014.rikubetsu01.R0/1149282
Indianapolis	39.86	−86.00	270	USA	doi:10.14291/tcon.ggg2014.indianapolis01.R0/1149164
Four Corners	36.80	−108.48	1643	USA	doi:10.14291/tcon.ggg2014.fourcorners01.R0/1149272
Lamont	36.60	−97.49	320	USA	doi:10.14291/tcon.ggg2014.lamont01.R0/1149159
Tsukuba	36.05	140.12	30	Japan	(120HR) doi:10.14291/tcon.ggg2014.tsukuba01.R0/1149281 (125HR) doi:10.14291/tcon.ggg2014.tsukuba02.R0/1149301
Edwards	34.96	−117.88	700	USA	doi:10.14291/tcon.ggg2014.edwards01.R0/1149289
JPL	34.20	−118.18	390	USA	doi:10.14291/tcon.ggg2014.jpl02.R0/1149297
Pasadena	34.14	−118.13	237	USA	doi:10.14291/tcon.ggg2014.pasadena01.R1/1182415
Saga	33.24	130.29	7	Japan	doi:10.14291/tcon.ggg2014.saga01.R0/1149283
Izaña	28.30	−16.50	2370	Tenerife, Canary Islands	doi:10.14291/tcon.ggg2014.izana01.R0/1149295
Ascension Island	−7.92	−14.33	31	South Atlantic Ocean	doi:10.14291/tcon.ggg2014.ascension01.R0/1149285
Darwin	−12.42	130.89	30	Australia	doi:10.14291/tcon.ggg2014.darwin01.R0/1149290
Reunion Island	−20.90	55.49	87	Indian Ocean	doi:10.14291/tcon.ggg2014.reunion01.R0/1149288
Wollongong	−34.41	150.88	30	Australia	doi:10.14291/tcon.ggg2014.wollongong01.R0/1149291
Lauder	−45.04	169.68	370	New Zealand	(120HR) doi:10.14291/tcon.ggg2014.lauder01.R0/1149293 (125HR) doi:10.14291/tcon.ggg2014.lauder02.R0/1149298

(or ΔXCH_4) and simultaneously retrieved auxiliary parameters obtained within $\pm 5^\circ$ latitude/longitude boxes centered at respective TCCON sites. The GOSAT data retrieved over land and ocean regions are described by green and blue dots, respectively. For instance, ΔXCO_2 has a significant negative correlation with the difference between the retrieved surface pressure and a priori surface pressure (ΔP_S ; Fig. 2b), which suggests that error in the surface pressure retrieval (ΔP_S) is, in part, responsible for the presence of the GOSAT XCO₂ biases. Thus, we examined the correlations between the GOSAT biases and more than 20 other parameters retrieved from GOSAT TANSO-FTS, and investigated which combinations of available parameters led to a reduction of the GOSAT biases due to the linear regression. For the correction of XCO₂ retrievals, we selected four parameters to include in bias corrections; the retrieved aerosol optical depth (AOD), ΔP_S , air mass, and surface albedo for the O₂ A-band. The derived bias correction for XCO₂ is

$$X_{CO_2}^{modified} = X_{CO_2}^{retrieved} + C_0 - C_1(AOD - \overline{AOD}) - C_2(\Delta P_S - \overline{\Delta P_S}) - C_3(\text{airmass} - \overline{\text{airmass}}) - C_4(\text{albedo}_{O_2} - \overline{\text{albedo}_{O_2}}). \quad (1)$$

However, only the retrieved AOD was selected for XCH₄ retrievals. The bias correction for XCH₄ is

$$X_{CH_4}^{modified} = X_{CH_4}^{retrieved} + C_0 - C_1(AOD - \overline{AOD}). \quad (2)$$

Here, $X_{CO_2}^{retrieved}$ and $X_{CH_4}^{retrieved}$ are the GOSAT XCO₂ and XCH₄ retrievals, respectively (i.e., uncorrected GOSAT data). $X_{CO_2}^{modified}$ and $X_{CH_4}^{modified}$ denote the corrected GOSAT XCO₂ and XCH₄ data, respectively. AOD represents the retrieved aerosol optical depth, and ΔP_S is the difference between the retrieved surface pressure and the a priori surface pressure. Air mass is a simple function of the solar zenith angle θ_Z and the satellite-viewing angle θ_V and can be approximated as

$$\text{airmass} = \frac{1}{\cos \theta_Z} + \frac{1}{\cos \theta_V}. \quad (3)$$

In addition, albedo_{O_2} is the surface albedo for the O₂ A-band, which is retrieved only for land. The overbars denote averages of all GOSAT data used for the regression analysis. C_0 is the regression coefficient for the bias, and C_1 , C_2 , C_3 , and C_4 are the regression coefficients for the respective parameters, that are used for the correction of GOSAT data. As described in the next paragraph, we determined these regression coefficients separately for land and ocean regions.

Table 2. Basic information on the aircraft observation sites used for validation of the GOSAT data.

(a) CONTRAIL					
Site code	Latitude (deg. N)	Longitude (deg. E)	Elevation (m)	Region	Site name
LHR	51.5	−0.5	24	London	Heathrow Airport
YVR	49.2	−123.2	4	Vancouver	Vancouver International Airport
MXP	45.6	8.7	24	Milan	Milan–Malpensa International Airport
FCO	41.8	12.3	5	Rome	Fiumicino Airport
ICN	37.5	126.5	7	Incheon	Incheon International Airport
NRT	35.8	140.4	43	Narita	Narita International Airport
HND	35.6	139.8	6	Haneda	Tokyo International Airport
NGO	34.9	136.8	5	Nagoya	Chubu Centrair International Airport
KIX	34.4	135.2	0	Kansai	Kansai International Airport
HNL	21.3	−157.9	4	Honolulu	Honolulu International Airport
BKK	13.7	100.7	2	Bangkok	Suvarnabhumi International Airport
SIN	1.4	104.0	7	Singapore	Singapore Changi International Airport
CGK	−6.1	106.7	10	Jakarta	Jakarta International Soekarno–Hatta Airport
SYD	−33.9	151.2	6	Sydney	Kingsford Smith Airport
(b) NOAA					
DND	48.4	−97.8	464	USA	Dahlen, North Dakota
LEF	45.9	−90.3	472	USA	Park Falls, Wisconsin
NHA	43.0	−70.6	0	USA	Worcester, Massachusetts
WBI	41.7	−91.4	242	USA	West Branch, Iowa
THD	41.1	−124.2	107	USA	Trinidad Head, California
BNE	40.8	−97.2	466	USA	Beaver Crossing, Nebraska
CAR	40.4	−104.3	1740	USA	Briggsdale, Colorado
HIL	40.1	−87.9	202	USA	Homer, Illinois
AAO	40.1	−88.6	213	USA	Airborne Aerosol Observing, Illinois
SCA	32.8	−79.6	0	USA	Charleston, South Carolina
TGC	27.7	−96.9	0	USA	Sinton, Texas
RTA	−21.3	−159.8	3	Cook Islands	Rarotonga
(c) DOE					
SGP	36.8	−97.5	314	USA	Southern Great Plains, Oklahoma
(d) NIES					
YAK	62	130	136	Russia	Yakutsk
SGM	35.1	139.3	0	Japan	Sagami Bay
(e) JMA					
MNM	24.3	154.0	8	Japan	Minamitorishima
(f) HIPPO					
HPA	49	−110	1040	USA	northeastern part of Great Falls, Montana
HPB	−28	−166	0	South Pacific Ocean	southwestern part of Rarotonga
HPC	−23	−161	0	South Pacific Ocean	southwestern part of Rarotonga
HPD	−33	158	0	Australia	eastern part of Lord Howe
HPE	−33	152	0	Australia	east coast of Newcastle
HPF	−20	156	0	Coral Sea	western part of Chesterfield Islands
HPG	−5	−167	0	Kiribati	western part of Enderbury
HPH	−37	179	0	New Zealand	northeastern part of Bay of Plenty
HPI	−36	179	0	New Zealand	northeastern part of Bay of Plenty
(g) NIES-JAXA					
TKB	36.1	140.1	31	Japan	Tsukuba

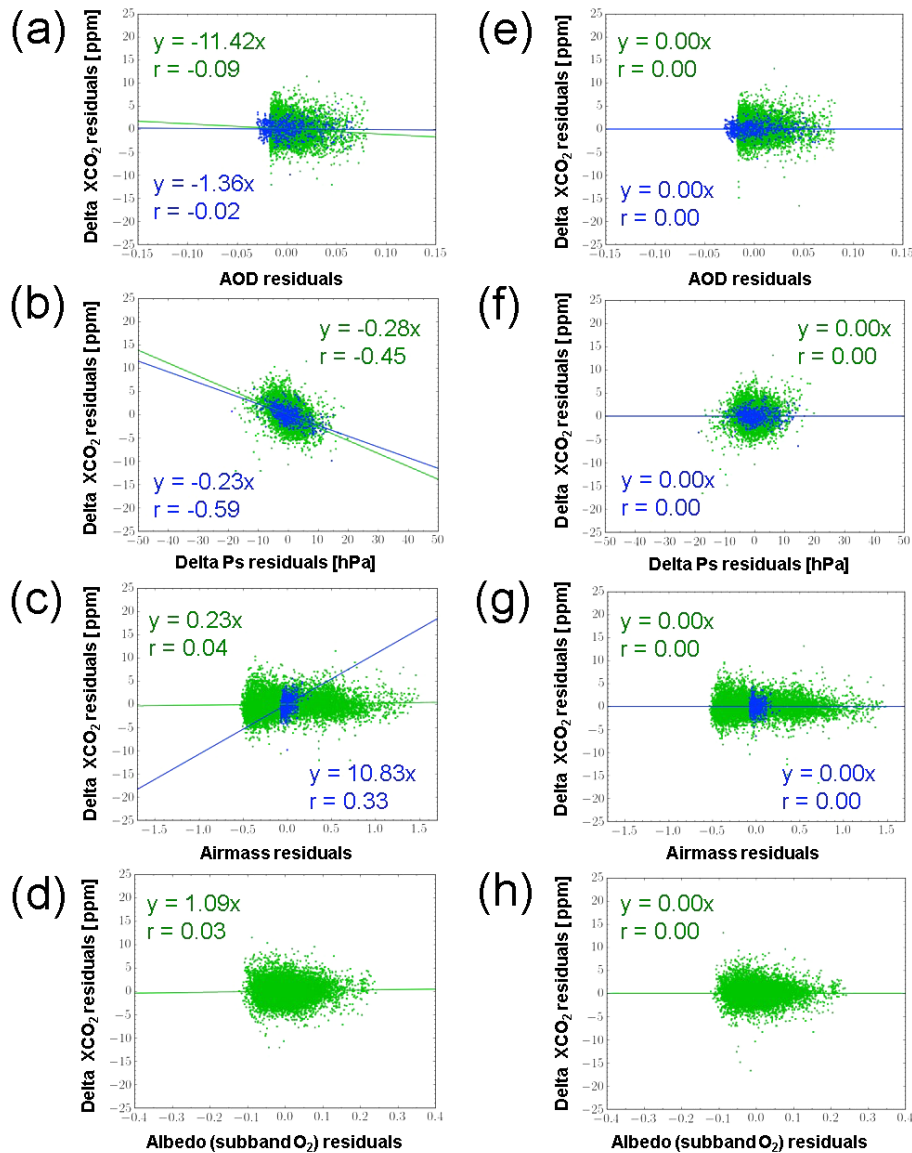


Figure 2. Scatter diagrams between ΔXCO_2 calculated from uncorrected GOSAT data and (a) the retrieved aerosol optical depth, (b) the difference between the retrieved and a priori surface pressures, (c) airmass, and (d) surface albedo for the O₂ A-band. Scatter diagrams between ΔXCO_2 calculated from corrected GOSAT data and (e) the retrieved aerosol optical depth, (f) the difference between the retrieved and a priori surface pressures, (g) airmass, and (h) surface albedo for the O₂ A-band. Green (blue) dots and lines indicate the GOSAT data and regression lines over land (ocean) regions.

Here, we discuss the spatiotemporal co-location criteria for calculations of the regression analyses. The ideal co-location criteria should be measurements at the same place during the same time (Zhou et al., 2016). In general, geographical co-location defines a spatiotemporal neighborhood region near the location of interest, and collects summary statistics (hereafter referred to as “geophysical co-location method”, Cogan et al., 2012; Nguyen et al., 2014; Zhou et al., 2016). A disadvantage of the geophysical co-location method is that the number of matched data can become small when the spatiotemporal criteria are somewhat

small. Therefore, several sophisticated methods were devised to obtain a sufficient number of co-located data. Following Keppel-Aleks et al. (2011) who implied a relationship between meridional gradients of free-tropospheric potential temperature and CO₂ concentrations in mid-latitudes over the Northern Hemisphere, Wunch et al. (2011b) used the distribution of potential temperature at 700 hPa when defining the co-location criteria in the Northern Hemisphere. Expansively, Nguyen et al. (2014) utilized a modified Euclidean distance weighted average of distance, time, and temperature at 700 hPa. Since this method is based on the fact that the

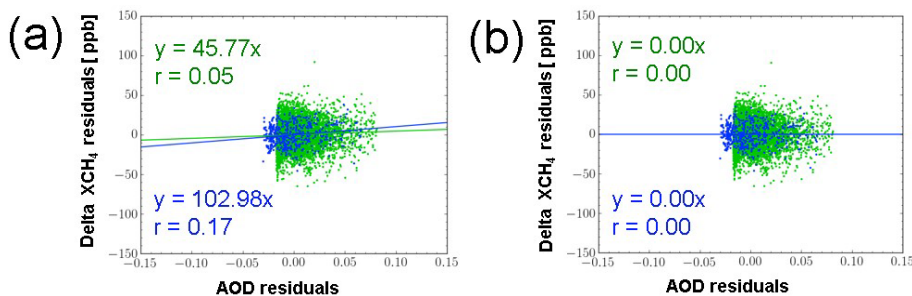


Figure 3. Scatter diagrams between ΔXCH_4 calculated from (a) uncorrected and (b) corrected GOSAT data and the retrieved aerosol optical depth. Green (blue) dots and lines indicate the GOSAT data and the regression lines over land (ocean) regions.

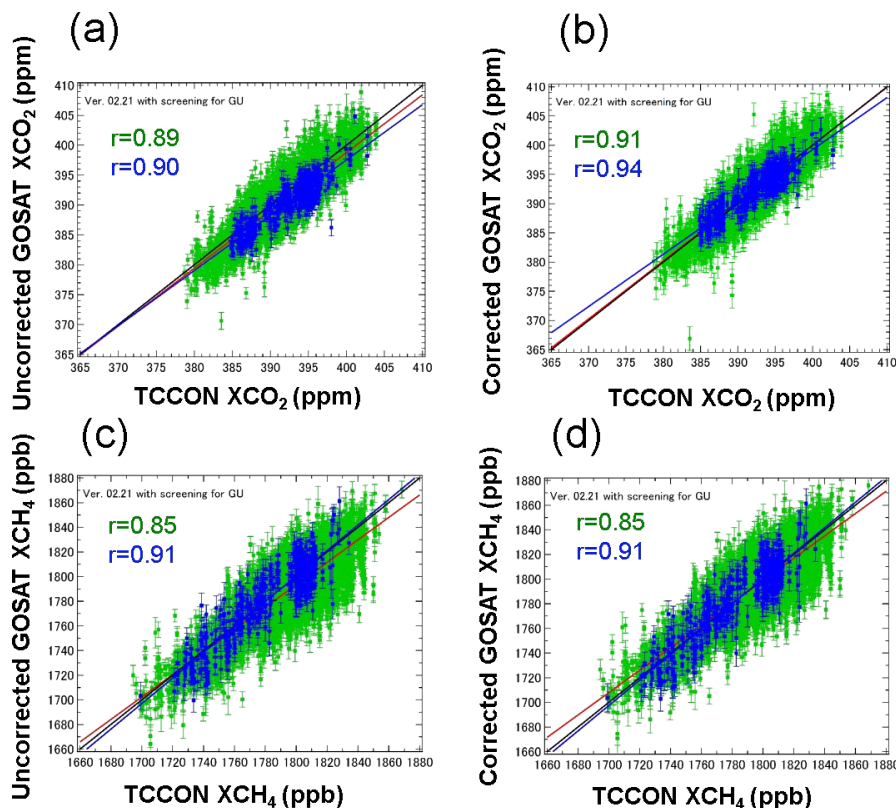


Figure 4. Scatter diagrams between (a) uncorrected and (b) corrected GOSAT XCO₂ observed within $\pm 5^\circ$ latitude/longitude boxes (centered at each TCCON site) and TCCON XCO₂ measured on the same day. (c, d), same as (a) and (b) for XCH₄. Green and blue dots indicate GOSAT data obtained over land and ocean regions, respectively. Red and blue lines denote the regression lines, statistically significant at the 99 % level, over land and ocean regions, respectively. Black lines show the one-to-one correspondence.

distribution of potential temperature at 700 hPa is deeply related to that of CO₂ density in the Northern Hemisphere, it is hard to apply this method to defining the co-location criteria in the low latitudes over the Northern Hemisphere and in the Southern Hemisphere. In addition, this method is not applicable to XCH₄. Guerlet et al. (2013) and Lindqvist et al. (2015) were based on the distribution of XCO₂ simulated by atmospheric transport model (e.g., the region where there is a modeled XCO₂ value within ± 0.5 ppm of standard deviation for the modeled value at the observation site). This can

lead to much larger matched data and be applied to the entire globe including the Southern Hemisphere. However, reliable XCH₄ modeled data are hard to obtain, and the sophisticated method for XCH₄ remains to be established. In this study, 5 years of GOSAT SWIR V02.21 XCO₂ and XCH₄ data are used for the validation and correction. Because the number of available TCCON site has rapidly increased after the GOSAT launch, we can obtain enough matched data by the geophysical co-location method. Therefore, in this study, the coefficients C_0 – C_4 were determined as follows:

Table 3. Values and errors of the regression coefficients for (a) XCO₂ and (b) XCH₄ retrievals calculated by multiple linear regression. The units of C_0 , C_1 , C_2 , C_3 , and C_4 for XCO₂ are (ppm), (ppm/units of AOD), (ppm/hPa), (ppm/airmass), and (ppm/units of albedo), respectively. The units of C_0 and C_1 for XCH₄ are (ppb) and (ppb/units of AOD), respectively.

(a)				
XCO ₂	Land		Ocean	
	Values	Errors	Values	Errors
C_0	0.865	0.021	1.903	0.055
C_1	-7.793	1.357	15.493	2.725
C_2	-0.282	0.006	-0.237	0.013
C_3	0.023	0.064	8.602	1.060
C_4	-2.036	0.433	-	-
(b)				
XCH ₄	Land		Ocean	
	Values	Errors	Values	Errors
C_0	6.0	0.2	0.2	0.6
C_1	45.8	10.0	103.0	26.4

To prepare the TCCON XCO₂ and XCH₄ as reference values for the multiple regression analysis, we made a connection between the GOSAT data retrieved within $\pm 5^\circ$ latitude/longitude boxes centered at respective TCCON sites and mean values of TCCON data (GGG2014 version) observed within ± 30 min of the GOSAT overpass time. Table 3 shows the regression coefficients obtained via the multiple linear regression analyses. Averages and the standard deviations (SD) of the differences between uncorrected GOSAT data and TCCON data at each site are listed in Table 4 for XCO₂ and Table 5 for XCH₄. Figure 4a and c are scatter diagrams between uncorrected GOSAT data and TCCON data at all TCCON sites for XCO₂ and XCH₄, respectively. For XCO₂, we identify 8245 samples for land and 544 samples for ocean that satisfy the coincident criteria. We find that global mean biases of GOSAT XCO₂ retrievals (i.e., uncorrected GOSAT XCO₂) over land and ocean regions against the TCCON data were -0.86 ppm (SD = 2.18 ppm) and -1.90 ppm (SD = 1.72 ppm), respectively (Table 4). The average and standard deviation of the GOSAT biases derived from respective TCCON sites (hereafter referred to as station bias) over land are -0.43 ppm and 0.87 ppm, respectively. Correlation coefficients between two XCO₂ data sets were 0.89 over land and 0.90 over ocean (Fig. 4a). The mean biases of uncorrected GOSAT XCH₄ over land and ocean regions were -6.0 ppb (SD = 15.2 ppb) and -0.2 ppb (SD = 13.4 ppb), respectively (Table 5). Correlation coefficients between both XCH₄ data sets were 0.85 over land and 0.91 over ocean (Fig. 4c). The results over land are similar to those of Yoshida et al. (2013) who validated GOSAT XCO₂ and XCH₄ data (Ver. 02.xx), although the versions of the TC-

CON data used in their study (the previous GGG2012 version) and our present study differ. Conducting the regression analysis using Eqs. (1) and (2), the regression coefficients for correction of GOSAT XCO₂ (and XCH₄) were determined separately for land and ocean regions (Table 3). Because surface albedo is not retrieved over ocean, the terms including C_4 in Eq. (1) were neglected for determining the regression coefficients for XCO₂ over ocean. The GOSAT data were obtained through two different TANSO-FTS modes: medium gain (Gain-M) utilized over bright land surfaces including the Sahara Desert and high gain (Gain-H) used elsewhere (Yoshida et al., 2013). Note that the regression coefficients are calculated from GOSAT data retrieved within $\pm 5^\circ$ boxes centered at 20 TCCON sites, that are located in Gain-H regions even though we aim to correct GOSAT XCO₂ and XCH₄ data from around the world, including Gain-H and Gain-M regions. Additionally, we take the mean difference between TCCON XCH₄ and aircraft-based XCH₄ into account when calculating the coefficients C_0 over land and ocean for XCH₄. In a comparative analysis at four locations, Inoue et al. (2014) showed that aircraft-based XCH₄ was 8.6 ppb smaller than TCCON XCH₄ on average. Consequently, in this study, we used the values for C_0 shown in Table 3b (i.e., 6.0 ppb over land and 0.2 ppb over ocean) for the correction of GOSAT XCH₄ when comparing GOSAT XCH₄ with TCCON XCH₄. In contrast, the values for C_0 shown in Table 3b with 8.6 ppb subtracted (i.e., -2.6 ppb over land and -8.4 ppb over ocean) were used when comparing the GOSAT XCH₄ with the aircraft-based XCH₄. Figures 2e–h and 3b are scatter diagrams between the biases of GOSAT data (Δ XCO₂ and Δ XCH₄) corrected by these regression coefficients C_0 – C_4 (Table 3) and simultaneously retrieved parameters. After correction, the correlation coefficients between Δ XCO₂ (or Δ XCH₄) and respective parameters were approximately zero.

We compare the GOSAT XCO₂ and XCH₄ corrected using the regression coefficients to the TCCON XCO₂ and XCH₄ (Tables 4–5, and Figs. 4b and d). Using this empirical correction, the global mean biases of GOSAT XCO₂ relative to the TCCON data became zero over both land (change from -0.86 to 0.00 ppm) and ocean (-1.90 to -0.01 ppm). Correlation coefficients between GOSAT XCO₂ and TCCON XCO₂ became somewhat higher over land (0.89 to 0.91). Table 5 shows that the mean biases of GOSAT XCH₄ also became zero over both land (-6.0 to 0.0 ppb) and ocean (-0.2 to -0.1 ppb). Clearly, as expected, the GOSAT XCO₂ and XCH₄ biases were reduced after correction. This, of course, is a natural consequence because the GOSAT data approached the TCCON values after applying the corrections. Therefore, in the next section, we validate the GOSAT XCO₂ and XCH₄ corrected by TCCON data using independent aircraft measurement data instead of TCCON data.

Table 4. The average and standard deviation of the differences between uncorrected/corrected GOSAT XCO₂ and TCCON XCO₂ at each TCCON site. The GOSAT data were retrieved over (a) land and (b) ocean regions within $\pm 5^\circ$ latitude/longitude boxes centered at each site. The averages and standard deviations of the differences of the matched data at all TCCON sites (single scan) and those of the station biases are also shown in the second row from the bottom and the bottom row of the table, respectively.

(a) Land		Differences between uncorrected GOSAT XCO ₂ and TCCON XCO ₂		Differences between corrected GOSAT XCO ₂ and TCCON XCO ₂	
Site	number	average (ppm)	SD (ppm)	average (ppm)	SD (ppm)
Sodankylä	152	-0.03	1.93	0.48	1.92
Białystok	305	-0.18	2.22	0.79	2.05
Bremen	62	-0.10	1.98	0.46	1.52
Karlsruhe	229	0.35	2.27	0.85	2.01
Orléans	402	-0.26	2.00	0.24	1.82
Garmisch	326	0.23	2.42	0.70	2.17
Park Falls	482	-0.50	2.15	0.37	1.90
Rikubetsu	7	-0.92	1.32	-0.46	0.84
Indianapolis	158	-0.03	1.69	0.37	1.37
Four Corners	142	-1.17	1.95	0.07	1.87
Lamont	2767	-1.72	1.79	-0.49	1.61
Tsukuba	419	1.55	2.37	1.67	2.24
Edwards	38	-1.35	1.46	-0.49	1.10
JPL	264	-2.32	2.32	-1.01	2.33
Pasadena	109	-0.41	2.12	0.22	2.45
Saga	128	0.37	2.37	0.66	2.31
Izaña	56	0.47	1.34	0.92	1.04
Darwin	926	-1.16	1.51	-0.25	1.34
Wollongong	1071	-0.68	2.25	-0.05	2.25
Lauder	202	-0.77	1.79	-0.23	1.83
Total (single scan)	8245	-0.86	2.18	0.00	1.94
Total (station bias)	20	-0.43	0.87	0.24	0.62
(b) Ocean		Differences between uncorrected GOSAT XCO ₂ and TCCON XCO ₂		Differences between corrected GOSAT XCO ₂ and TCCON XCO ₂	
Site	number	average (ppm)	SD (ppm)	average (ppm)	SD (ppm)
Garmisch	5	-0.55	0.49	-0.67	0.83
Tsukuba	2	-2.87	2.35	-4.01	0.65
JPL	8	-4.71	3.64	-1.36	2.47
Saga	14	-1.15	2.56	-0.34	1.56
Izaña	50	-1.50	1.36	0.23	1.17
Ascension Island	234	-1.93	1.62	-0.17	1.18
Darwin	85	-1.64	1.86	0.54	1.56
Reunion Island	43	-2.19	1.43	-0.08	0.95
Wollongong	97	-2.04	1.49	0.05	1.04
Lauder	6	-2.54	2.32	0.53	0.87
Total (single scan)	544	-1.90	1.72	-0.01	1.29
Total (station bias)	10	-2.11	1.13	-0.53	1.35

Table 5. The average and standard deviation of the differences between uncorrected/corrected GOSAT XCH₄ and TCCON XCH₄ at each TCCON site. The GOSAT data were retrieved over (a) land and (b) ocean regions within $\pm 5^\circ$ latitude/longitude boxes centered at each site. The averages and standard deviations of the differences of the matched data at all TCCON sites (single scan) and those of the station biases are also shown in the second row from the bottom and the bottom row of the table, respectively.

(a) Land		Differences between uncorrected GOSAT XCH ₄ and TCCON XCH ₄		Differences between corrected GOSAT XCH ₄ and TCCON XCH ₄	
Site	number	average (ppb)	SD (ppb)	average (ppb)	SD (ppb)
Sodankylä	152	-2.3	11.4	3.8	11.4
Białystok	305	0.5	12.9	6.2	12.9
Bremen	62	-1.6	12.7	4.2	12.7
Karlsruhe	229	-0.9	15.3	5.0	15.3
Orléans	402	-3.9	12.7	2.0	12.7
Garmisch	326	6.2	16.3	11.9	16.3
Park Falls	482	3.3	13.9	9.2	13.9
Rikubetsu	7	4.1	8.6	9.7	8.8
Indianapolis	158	-1.4	10.9	5.0	10.9
Four Corners	142	-8.9	14.2	-3.0	14.3
Lamont	2767	-9.0	15.1	-2.9	15.2
Tsukuba	419	1.9	13.2	7.5	13.1
Edwards	38	-19.5	16.8	-13.2	16.7
JPL	264	-21.1	19.4	-15.1	19.4
Pasadena	109	-8.1	15.3	-1.8	15.3
Saga	128	-5.3	14.4	0.0	14.4
Izaña	56	15.4	12.7	20.1	13.1
Darwin	926	-8.6	8.9	-2.4	9.1
Wollongong	1076	-9.1	14.5	-2.8	14.7
Lauder	208	-3.9	11.3	2.4	11.2
Total (single scan)	8256	-6.0	15.2	0.0	15.2
Total (station bias)	20	-3.6	8.4	2.3	8.1
(b) Ocean		Differences between uncorrected GOSAT XCH ₄ and TCCON XCH ₄		Differences between corrected GOSAT XCH ₄ and TCCON XCH ₄	
Site	number	average (ppb)	SD (ppb)	average (ppb)	SD (ppb)
Garmisch	5	18.7	11.0	20.4	11.0
Tsukuba	2	21.9	16.0	21.2	17.2
JPL	8	-17.1	13.1	-17.4	12.9
Saga	14	0.7	17.0	-0.3	17.0
Izaña	50	14.8	7.7	14.1	8.4
Ascension Island	234	-1.0	11.5	-0.6	11.2
Darwin	85	4.1	13.2	3.0	13.3
Reunion Island	43	-0.4	8.3	0.1	8.9
Wollongong	97	-9.7	11.1	-8.6	11.7
Lauder	6	-5.9	11.9	-4.3	12.3
Total (single scan)	544	-0.2	13.4	-0.1	13.2
Total (station bias)	10	2.6	12.6	2.8	12.5

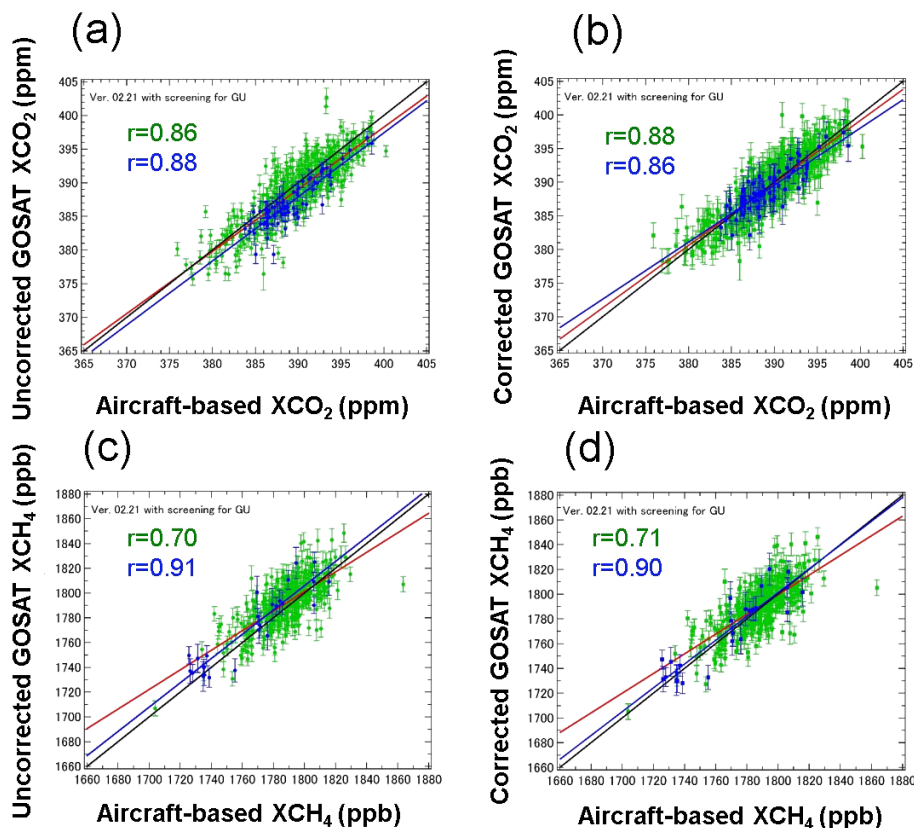


Figure 5. Scatter diagrams between (a) uncorrected and (b) corrected GOSAT XCO₂ observed within $\pm 5^\circ$ latitude/longitude boxes (centered on each aircraft profile) and aircraft-based XCO₂ observed on the same day. (c, d), same as (a) and (b) for XCH₄. Green and blue dots indicate the GOSAT data obtained over land and ocean regions, respectively. Red and blue lines denote the regression lines, statistically significant at the 99 % level, over land and ocean regions, respectively. Black lines show the one-to-one correspondence.

3.2 Comparisons between uncorrected/corrected GOSAT data and aircraft-based data

To confirm the effectiveness of the empirical correction, we compare uncorrected/corrected GOSAT data with aircraft-based data. Figure 5 shows scatter diagrams between uncorrected/corrected GOSAT data and aircraft-based data at all aircraft observation sites. Tables 6 and 7 indicate the differences between uncorrected/corrected GOSAT data and aircraft-based data for XCO₂ and XCH₄ at each aircraft site, respectively. The average differences between uncorrected GOSAT XCO₂ and aircraft-based XCO₂ over land and ocean within $\pm 5^\circ$ latitude/longitude boxes were -0.85 ppm (SD = 2.48 ppm) and -2.08 ppm (SD = 1.69 ppm), respectively (Table 6). The correction reduced the mean biases of GOSAT XCO₂ to below twentieth over land (-0.85 to -0.04 ppm) and to below one-sixth over ocean (-2.08 to -0.32 ppm). The averages of the XCO₂ station bias over land and ocean are also smaller after correction. The correlation coefficients between GOSAT XCO₂ and aircraft-based XCO₂ over land became higher after correction (0.86 to 0.88). We here compare our results to those by other XCO₂

bias correction study. Cogan et al. (2012) showed the annual mean global difference to be reduced by about half (-1.22 to -0.68 ppm) and the correlation coefficients to increase from 0.61 to 0.74. Thus, our correction method is effective for removing the biases significantly. For XCH₄, the average differences between uncorrected GOSAT XCH₄ and aircraft-based XCH₄ over land and ocean were 4.5 ppb (SD = 15.2 ppb) and 6.6 ppb (SD = 12.8 ppb), respectively (Table 7). The global mean biases of corrected GOSAT XCH₄ relative to aircraft measurements were also reduced by half over land (4.5 to 2.2 ppb) and reduced to about one-quarter over ocean (6.6 to -1.7 ppb). The correlation coefficients between GOSAT XCH₄ and aircraft-based XCH₄ over land became higher (0.70 to 0.71). Thus, the bias correction improves the accuracy and precision of the GOSAT data for both XCO₂ and XCH₄.

3.3 Spatial distributions of uncorrected/corrected GOSAT data

We next applied the regression coefficients C_0 – C_4 calculated from samples around only 22 TCCON sites to all GOSAT XCO₂ and XCH₄ data around the world, and we examined

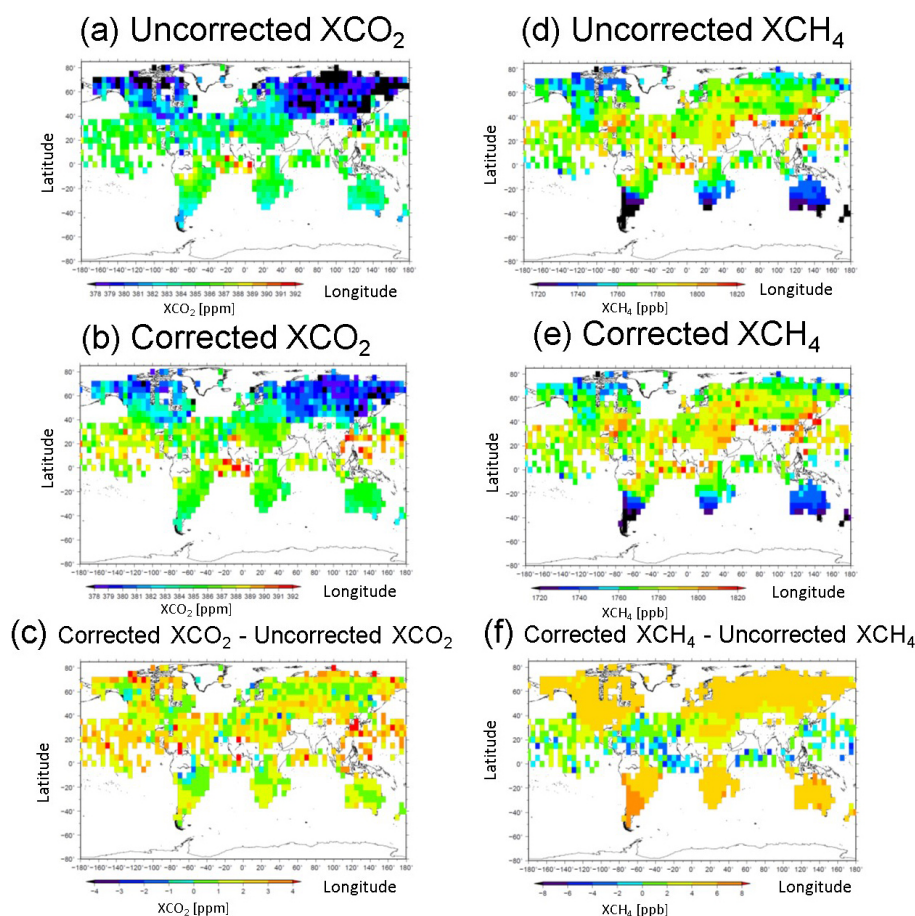


Figure 6. Global maps of the monthly means of (a) uncorrected and (b) corrected GOSAT XCO₂, and (d) uncorrected and (e) corrected GOSAT XCH₄ in July 2009. GOSAT XCO₂ and XCH₄ data were binned in 5° by 5° grid elements. The differences between corrected and uncorrected (c) GOSAT XCO₂ and (f) GOSAT XCH₄.

how the spatial distributions of GOSAT data changed due to this empirical correction. Figure 6a and b indicate the spatial distributions of the monthly means of uncorrected GOSAT XCO₂ and corrected GOSAT XCO₂, respectively, in July 2009. The GOSAT XCO₂ data were binned in 5° by 5° grid elements. In the northern summer, the CO₂ concentration over Siberia is significantly lower due to forest absorption of CO₂ through photosynthesis (e.g., Nakazawa et al., 1997; Guerlet et al., 2013). The differences between corrected GOSAT XCO₂ and uncorrected GOSAT XCO₂ are shown in Fig. 6c. As noted above, GOSAT XCO₂ has a negative bias of about 1–2 ppm over land and ocean regions. Therefore, the bias correction increases XCO₂ in most parts of the world (Fig. 6c). In the middle of South America and southern Africa, however, GOSAT XCO₂ became smaller after correction. The differences between corrected XCO₂ and uncorrected XCO₂ were about 2–4 ppm and less than 2 ppm in western part and eastern part of North America, respectively (Fig. 6c). This larger spatial gradient over North America is consistent with the result of Guerlet et

al. (2013), though the months analyzed in their study (August and September) and our present study (July) differ. This feature over North America may be due to the differences in the type and condition of vegetation which have a strong impact on the surface albedo. Finally, this can have an influence on the estimation of regional CO₂ fluxes over North America by inverse analysis. We next focus on the spatial distributions of uncorrected/corrected GOSAT XCH₄ in July 2009 (Fig. 6d and e). Figure 6d shows that CH₄ concentrations in the Northern Hemisphere are higher than those in the Southern Hemisphere. In particular, there are distinct features of high CH₄ concentrations around the eastern United States, the Middle East, western Siberia, and East Asia in the Northern Hemisphere and low CH₄ concentrations over southern South America, southern Africa, and Australia, with a larger gradient in the Southern Hemisphere. After correction, GOSAT XCH₄ became 4–8 ppb higher over most land regions (Fig. 6f), consistent with comparisons to the TCCON data over land (Sect. 3.1). XCH₄ over the ocean became smaller at low latitudes in the Northern Hemisphere

Table 6. The average and standard deviation of the differences between uncorrected/corrected GOSAT XCO₂ and aircraft-based XCO₂ at each aircraft observation site. The GOSAT data were retrieved over (a) land and (b) ocean regions within $\pm 5^\circ$ latitude/longitude boxes centered at each site. The averages and standard deviations of the differences of the matched data at all aircraft observation sites (single scan) and those of the station biases are also shown in the second row from the bottom and the bottom row of the table, respectively.

(a) Land		Differences between uncorrected GOSAT XCO ₂ and aircraft-based XCO ₂		Differences between corrected GOSAT XCO ₂ and aircraft-based XCO ₂	
Site	number	average (ppm)	SD (ppm)	average (ppm)	SD (ppm)
LHR	3	-3.24	1.25	-2.09	0.66
YVR	7	-0.64	2.07	0.21	1.95
MXP	2	0.06	1.88	1.09	1.54
ICN	1	0.64	-	3.37	-
NRT	69	0.17	2.52	0.54	2.34
HND	2	-0.38	2.56	0.09	3.83
NGO	15	0.27	2.47	0.73	2.39
KIX	5	-1.01	3.25	-0.19	2.73
BKK	5	-2.90	3.86	-1.78	3.43
SYD	22	-1.19	2.48	-0.62	2.19
DND	11	-1.37	1.74	-0.47	1.48
LEF	34	0.02	2.77	0.66	2.79
NHA	25	0.27	1.64	0.44	1.69
WBI	23	-0.95	2.92	0.17	2.43
THD	4	-1.99	1.64	-0.06	1.13
BNE	6	-1.15	2.48	0.15	2.02
CAR	51	-2.17	2.20	-0.73	1.93
HIL	37	-2.16	1.96	-1.25	2.33
AAO	20	-0.18	2.32	0.64	2.28
SCA	22	-0.31	1.56	-0.01	1.60
TGC	15	-0.51	2.53	0.45	3.02
SGP	68	-1.61	2.20	-0.43	2.03
YAK	3	1.70	2.89	1.79	2.59
SGM	6	1.02	3.11	1.63	2.71
HPA	1	-2.84	-	-0.76	-
HPH	1	-1.91	-	-0.71	-
TKB	11	0.11	1.89	0.17	1.68
Total (single scan)	469	-0.85	2.48	-0.04	2.28
Total (station bias)	27	-0.82	1.24	0.11	1.11
(b) Ocean		Differences between uncorrected GOSAT XCO ₂ and aircraft-based XCO ₂		Differences between corrected GOSAT XCO ₂ and aircraft-based XCO ₂	
Site	number	average (ppm)	SD (ppm)	average (ppm)	SD (ppm)
FCO	1	0.12	-	-3.39	-
NRT	4	-4.27	3.24	-2.89	2.49
HND	1	0.86	-	2.51	-
NGO	3	-1.43	0.77	-0.02	0.58
KIX	4	-3.00	1.95	-1.86	1.56
HNL	19	-1.49	1.06	0.66	1.36
BKK	2	-3.40	0.96	-1.10	0.24
SIN	4	-2.33	1.70	0.06	2.05
CGK	2	-2.46	3.12	0.57	0.25
SYD	5	-1.52	1.28	-0.03	1.04
NHA	3	-1.56	1.07	-1.60	2.06
SCA	5	-2.67	2.05	-0.45	1.99
TGC	2	-2.36	0.12	-0.52	0.02
RTA	6	-2.93	1.75	-0.39	1.36
MNM	3	-1.39	0.61	-0.45	1.41
HPB	1	-0.16	-	0.86	-
HPD	1	-2.21	-	0.07	-
HPG	1	-3.29	-	-1.89	-
Total (single scan)	67	-2.08	1.69	-0.32	1.74
Total (station bias)	18	-1.97	1.31	-0.55	1.41

Table 7. The average and standard deviation of the differences between uncorrected/corrected GOSAT XCH₄ and aircraft-based XCH₄ at each aircraft observation site. The GOSAT data were retrieved over (a) land and (b) ocean regions within $\pm 5^\circ$ latitude/longitude boxes centered at each site. The averages and standard deviations of the differences of the matched data at all aircraft observation sites (single scan) and those of the station biases are also shown in the second row from the bottom and the bottom row of the table, respectively.

(a) Land		Differences between uncorrected GOSAT XCH ₄ and aircraft-based XCH ₄		Differences between corrected GOSAT XCH ₄ and aircraft-based XCH ₄	
Site	number	average (ppb)	SD (ppb)	average (ppb)	SD (ppb)
DND	12	7.3	10.0	5.0	10.0
LEF	33	9.3	19.9	7.1	19.8
NHA	26	7.4	14.6	5.2	14.4
WBI	19	5.3	12.7	2.7	13.2
THD	4	-15.6	20.3	-17.9	20.6
BNE	5	9.4	9.1	7.0	9.0
CAR	44	5.6	13.7	3.2	14.1
HIL	32	2.6	14.3	0.1	14.2
AAO	21	0.6	15.4	-2.1	15.3
SCA	20	7.9	12.4	5.9	12.4
TGC	13	8.7	16.2	6.7	16.4
SGP	69	0.4	15.7	-1.8	15.8
YAK	8	3.0	17.6	0.4	17.5
SGM	7	2.7	9.4	-0.3	9.3
HPA	1	-10.6	-	-12.5	-
HPI	1	3.0	-	1.5	-
TKB	11	10.8	12.4	8.5	12.0
Total (single scan)	326	4.5	15.2	2.2	15.3
Total (station bias)	17	3.4	7.0	1.1	7.0
(b) Ocean		Differences between uncorrected GOSAT XCH ₄ and aircraft-based XCH ₄		Differences between corrected GOSAT XCH ₄ and aircraft-based XCH ₄	
Site	number	average (ppb)	SD (ppb)	average (ppb)	SD (ppb)
NHA	3	24.2	10.9	16.7	10.1
SCA	5	-4.9	9.1	-13.6	9.6
TGC	2	9.5	2.3	3.1	2.8
RTA	7	5.2	14.5	-3.0	15.2
MNM	4	13.1	8.2	3.6	8.0
HPC	1	-2.2	-	-7.9	-
HPE	1	7.5	-	1.4	-
HPF	1	4.9	-	-3.5	-
HPG	1	-0.2	-	-13.8	-
Total (single scan)	25	6.6	12.8	-1.7	13.3
Total (station bias)	9	6.4	8.8	-1.9	9.6

(0°–20° N) such as the Atlantic Ocean, and became larger in mid-latitudes (20°–40° N).

It is difficult to evaluate whether the GOSAT data across the globe are improved by using the regression coefficients C₀–C₄ derived exclusively from around TCCON sites, due to the sparseness of the ground-based and aircraft mea-

surements in many regions around the world. Accordingly, we investigated the latitudinal distributions of the uncorrected/corrected GOSAT data, the TCCON data, and the aircraft-based data, and then compared the three data sets for July 2009 (Fig. 7). We prepared zonal-mean monthly averages of the GOSAT data retrieved in each 15° lati-

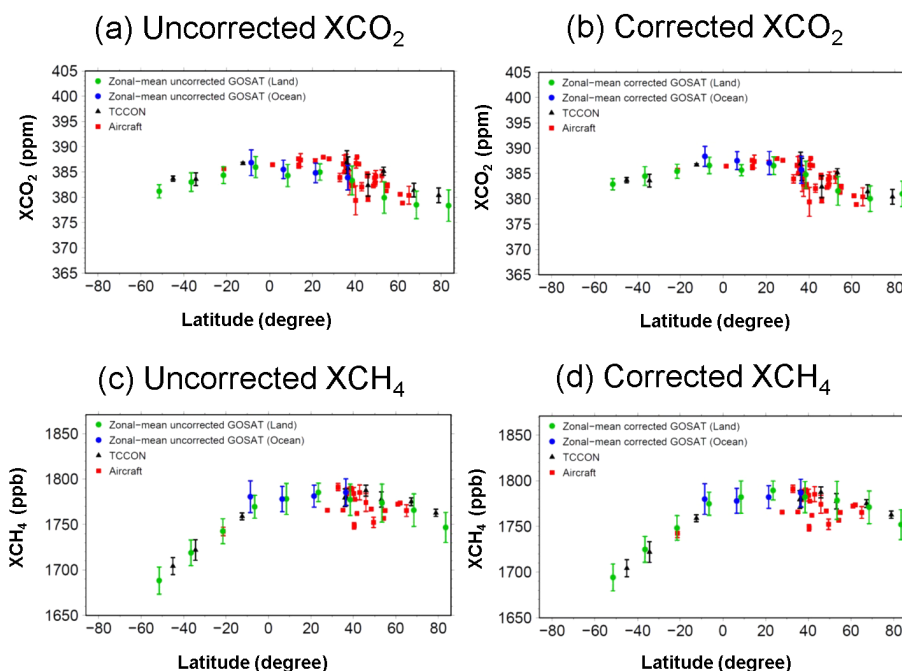


Figure 7. Latitudinal distributions of (a) uncorrected and (b) corrected GOSAT XCO₂, TCCON XCO₂, and aircraft-based XCO₂ in July 2009. Latitudinal distributions of (c) uncorrected and (d) corrected GOSAT XCH₄, TCCON XCH₄, and aircraft-based XCH₄ in July 2009. Green and blue circles indicate the zonal-mean GOSAT data retrieved over land and ocean regions, respectively. The black triangles and red squares denote the TCCON data and aircraft-based data, respectively, at each observation site. See text for details.

dinal band. For example, averages of GOSAT XCO₂ obtained over land and ocean regions within a latitudinal band from the equator to 15° N in July 2009 are represented by green and blue dots, respectively, around 7.5° N in Fig. 7a. The TCCON data are mean values measured within ±30 min of the GOSAT overpass time (e.g., about 12:50 pm local time in Tsukuba) on all days when TCCON data were obtained in July 2009. Aircraft-based data are monthly averages of all data obtained at each aircraft observation site. In July 2009, uncorrected GOSAT XCO₂ data were underestimated by about 1–2 ppm compared to the reference data (Fig. 7a). We found that corrected GOSAT XCO₂ was consistent with the TCCON XCO₂ and aircraft-based XCO₂ in both hemispheres, though the variability of aircraft-based XCO₂ was relatively large in mid-latitudes (Fig. 7b). Aircraft-based XCO₂ at the Honolulu site located around 20° N in July 2009 was 387.25 ppm. The uncorrected GOSAT XCO₂ and corrected GOSAT XCO₂ over the land regions around 20° N including Honolulu were 385.00 and 386.56 ppm, respectively, whereas those over the ocean regions were 384.82 and 387.07 ppm, respectively. By the correction, it was shown that GOSAT XCO₂ approached the aircraft-based XCO₂ value over both land and ocean. TCCON XCO₂ at Lauder was 383.71 ppm, and the uncorrected GOSAT XCO₂ and corrected GOSAT XCO₂ around 50° S including the Lauder site were 381.18 and 382.88 ppm, respectively. In the Southern Hemisphere, we found that GOSAT XCO₂ approached

the TCCON value by the correction. Figure 7c shows latitudinal distributions of uncorrected GOSAT XCH₄, TCCON XCH₄, and aircraft-based XCH₄. XCH₄ in the Northern Hemisphere is higher than that in the Southern Hemisphere in July (Fig. 7c), because the main CH₄ sources are terrestrial, including rice paddy fields and wetlands. In addition, the latitudinal variation in XCH₄ shows a larger meridional gradient in the Southern Hemisphere (Fig. 7c), which is consistent with the spatial distribution of XCH₄ (Fig. 6d). The uncorrected GOSAT XCH₄ was negatively biased against the TCCON data. The empirical correction resulted in a marked decrease in GOSAT XCH₄ biases on the same latitudinal bands as several TCCON sites (e.g., Ny-Ålesund, Sodankylä, and Lauder) over both hemispheres (Fig. 7d). For example, TCCON XCH₄ at the Ny-Ålesund site was 1762.9 ppb, and the uncorrected GOSAT XCH₄ and corrected GOSAT XCH₄ around 80° N including Ny-Ålesund were 1746.8 and 1752.0 ppb, respectively. By the bias correction, GOSAT XCH₄ approached the TCCON value. Thus, the correction method is very effective for reducing the biases of the GOSAT XCO₂ and XCH₄, from the standpoint of the spatial distributions.

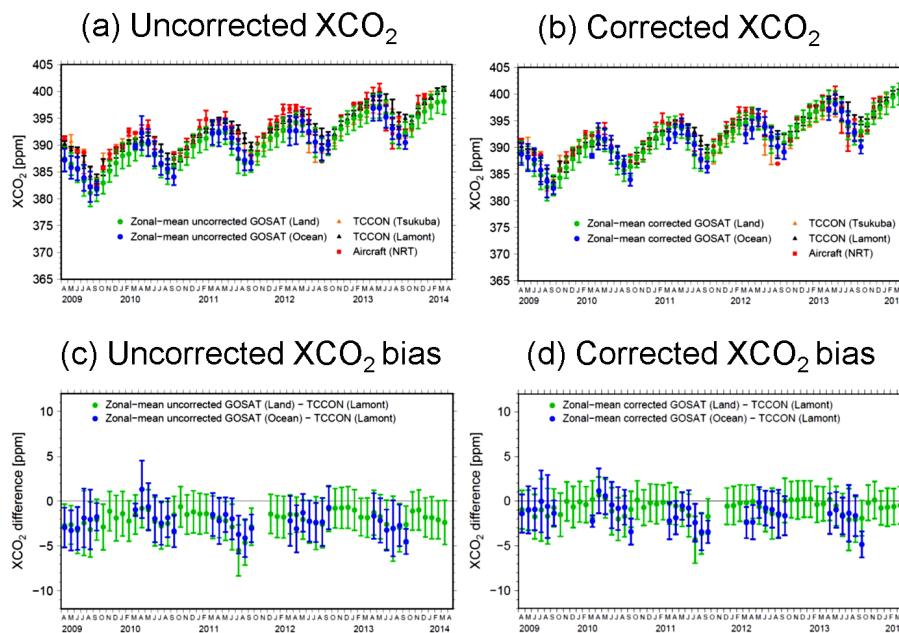


Figure 8. Temporal variations of (a) uncorrected and (b) corrected GOSAT XCO₂, TCCON XCO₂, and aircraft-based XCO₂. Green and blue circles in (a) and (b) indicate the monthly zonal-mean GOSAT data retrieved over land and ocean regions, respectively, within a 30°–45° N latitudinal band. The orange triangles, black triangles, and red squares in (a) and (b) denote the TCCON XCO₂ at Tsukuba and Lamont, and aircraft-based XCO₂ at Narita, respectively. Temporal variations of the differences between (c) uncorrected and (d) corrected GOSAT XCO₂ and TCCON XCO₂ at Lamont (GOSAT XCO₂ minus TCCON XCO₂) over land (green circles) and ocean (blue circles). See text for details.

3.4 Temporal behaviors of uncorrected/corrected GOSAT data and the GOSAT biases

Finally, we investigated temporal variations in GOSAT XCO₂ and XCH₄ data and the GOSAT biases. We focused on the 30°–45° N latitudinal band, which includes the Lamont site where most monthly data were available during the analysis period. Figure 8a shows the temporal variations of uncorrected GOSAT XCO₂, TCCON XCO₂ at Tsukuba and Lamont, and aircraft-based XCO₂ at Narita. Along with the example of July 2009 in Sect. 3.3, zonal-mean GOSAT XCO₂ retrieved over land and ocean regions within a 30°–45° N latitudinal band, TCCON XCO₂ and aircraft-based XCO₂ at several sites included in a 30°–45° N latitudinal band were calculated for all months during the analysis period. The temporal variations in the three data sets revealed that XCO₂ is higher in northern spring (April and May) and lower in August and September (Fig. 8a). XCO₂ has a seasonal amplitude of approximately 7–12 ppm at mid-latitudes over the Northern Hemisphere. In this study, the growth rate of uncorrected GOSAT XCO₂ was roughly 2.5 ppm yr⁻¹ from 2009 to 2013, while Inoue et al. (2013) showed that the growth rate of aircraft-based XCO₂ at most sites was about 2.0 ppm yr⁻¹ from 2007 to 2010. This is consistent with the rapid increase of CO₂ emissions over the last few years. After bias correction, the temporal variability in the GOSAT XCO₂ agrees with those of the TCCON and air-

craft measurements (Fig. 8b). To clarify it, we show the monthly variations of the differences between uncorrected and corrected GOSAT XCO₂ and TCCON XCO₂ at Lamont (Fig. 8c and d). The uncorrected GOSAT XCO₂ data were negatively biased (Fig. 8c); however, this time series has a seasonality wherein the negative biases of GOSAT XCO₂ become higher around July and August. After bias correction, the XCO₂ biases for many months approach zero, though the seasonality in the difference remains (Fig. 8d). Note that the TCCON XCO₂ data at Lamont are values at a particular location, while GOSAT XCO₂ data are zonal averaged values.

Figure 9a shows the temporal behavior of zonal-mean uncorrected GOSAT XCH₄ and XCH₄ at the Tsukuba and Lamont TCCON sites. GOSAT XCH₄ is higher in September and October, and lower in February and March than the reference data. Although the GOSAT XCH₄ data retrieved over land were negatively biased except for summer during the analysis period (Fig. 9a and c), the GOSAT XCH₄ biases were reduced as a result of the empirical correction (Fig. 9b and d). Consequently, we suggest that the bias correction method was effective for GOSAT XCO₂ and XCH₄.

4 Summary and conclusions

In this study, we correct XCO₂ and XCH₄ data (Ver. 02.21) retrieved from the GOSAT TANSO-FTS SWIR spectra. First, we conducted correlation analyses between the GOSAT biases and the simultaneously retrieved auxiliary pa-

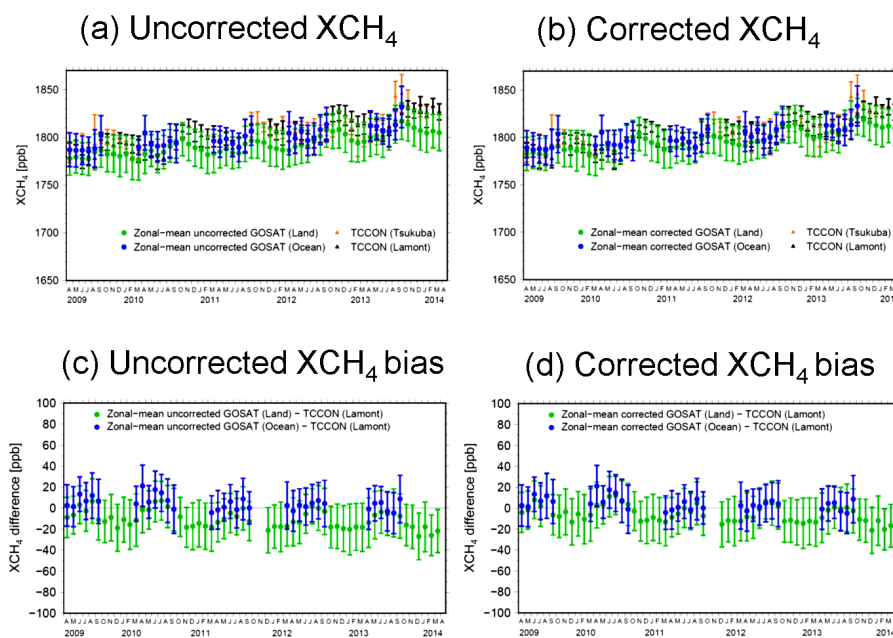


Figure 9. Temporal variations of (a) uncorrected and (b) corrected GOSAT XCH₄ and TCCON XCH₄. Green and blue circles in (a) and (b) indicate the monthly zonal-mean GOSAT data retrieved over land and ocean regions within a 30°–45° N latitudinal band, respectively. The orange and black triangles in (a) and (b) denote the TCCON XCH₄ at Tsukuba and Lamont, respectively. Temporal variations of the differences between (c) uncorrected and (d) corrected GOSAT XCH₄ and TCCON XCH₄ at Lamont (GOSAT XCH₄ minus TCCON XCH₄) over land (green circles) and ocean (blue circles). See text for details.

rameters, using GOSAT data around TCCON sites. Based on the results, we selected several parameters and determined the regression coefficients for the correction of GOSAT XCO₂ and XCH₄ for land and ocean regions separately. To evaluate the effectiveness of the bias correction method, the uncorrected/corrected GOSAT XCO₂ and XCH₄ data were compared to aircraft measurements provided by CONTRAIL, NOAA, DOE, NIES, JMA, the HIPPO project, and the NIES-JAXA joint campaign. After correction, biases of GOSAT XCO₂ were reduced by a factor of more than 20 over land and by a factor of 6 over ocean, while the biases of GOSAT XCH₄ were reduced by half over land and became by almost a quarter of their uncorrected values over ocean. We thus demonstrated that our empirical method using multiple linear regression is useful for the bias correction of GOSAT XCO₂ and XCH₄.

5 Data availability

The latest data processing and the auxiliary information on the GOSAT SWIR XCO₂ and XCH₄ data are described in GOSAT User Interface Gateway and can be obtained at http://data.gosat.nies.go.jp/GosatUserInterfaceGateway/gui/doc/documents/doc_en_docdist.html.

Acknowledgements. The authors thank the many staff members of Japan Airlines, the JAL Foundation, and JAMCO Tokyo for supporting the CONTRAIL project. We are grateful to the NOAA ESRL/GMD tall tower network (K. Davis, A. Desai, R. Teclaw, D. Baumann, and C. Stanier) for providing CO₂ tower data for Park Falls and West Branch. DOE flights were supported by the Office of Biological and Environmental Research of the US Department of Energy under contract no. DE-AC02-05CH11231 as part of the Atmospheric Radiation Measurement Program (ARM), ARM Aerial Facility, and Terrestrial Ecosystem Science Program. We gratefully thank many staff members of the Japan Ministry of Defense for supporting the JMA's ground-based and aircraft measurements. We also acknowledge the HIPPO team members for CO₂ and CH₄ profile data from HIPPO missions. The HIPPO program is supported by the National Science Foundation (NSF), and its operation is managed by the Earth Observing Laboratory (EOL) of the National Center for Atmospheric Research (NCAR). We also thank the Canadian Space Agency (CSA), which provides most of the funding support for ACE. We are grateful to the HALOE team for publishing their data for scientific use. This research was supported in part by the Environment Research and Technology Development Fund (2A-1102) of the Ministry of the Environment, Japan. TCCON measurements from Pasadena, Lamont, Park Falls and Darwin are funded by NASA grant NNX14AI60G and NASA Orbiting Carbon Observatory Program. We are grateful to the DOE ARM program for technical support of TCCON in Lamont and Darwin and to Jeff Ayers for technical support of the TCCON measurements in Park Falls. Darwin and Wollongong TCCON measurements are also supported by Australian Research

Council grant DP140101552 and Nicholas Deutscher is supported by an ARC-DECRA Fellowship, DE140100178. The University of Bremen acknowledges the support of the EU projects InGOS, and ICOS-INWIRE, and the Senate of Bremen for support of TCCON measurements in Białystok, Bremen, Ny-Ålesund, and Orléans. Operation of the Ascension Island site was funded by the Max Planck Society. Research at the FMI was supported by the Academy of Finland under grant no. 140408.

Edited by: I. Aben

Reviewed by: two anonymous referees

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