Authors are grateful to the anonymous referee for helpful and thoughtful comments. We added three co-authors based on additional analyses. Each comment is addressed individually below. The referee comments are recorded in normal type, and our responses are described in boldface type.

Atmos. Chem. Phys. Discuss., 13, C1522–C1522, 2013
www.atmos-chem-phys-discuss.net/13/C1522/2013/

Interactive comment on "Validation of XCO_2 derived from SWIR spectra of GOSAT TANSO-FTS with aircraft measurement data" by M. Inoue et al.

Anonymous Referee #1

Received and published: 18 April 2013

Please find my review of Inoue et al. 2013 in the supplement.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/13/C1522/2013/acpd-13-C1522-2013-supplement.pdf

Interactive comment on Atmos. Chem. Phys. Discuss., 13, 3203, 2013.

Review of "Validation of XCO2 derived from SWIR spectra of GOSAT TANSO-FTS with aircraft measurement data" by M. Inoue, et al. ACPD, 2013

Overview

This paper describes a reasonably thorough intercomparison of XCO2 as calculated by aircraft versus that from the TANSO-FTS instrument aboard GOSAT. The aircraft data are a synthesis of profiles from the CONTRAIL, NOAA, and NIES measurement programs The GOSAT-derived XCO2 are taken from the ver 02.00 NIES product. The authors find that aircraft and GOSAT XCO2 values are in generally good agreement, with GOSAT exhibiting a low bias of about -1 to -2 ppm, and a 1-sigma scatter of "1-3 ppm".

General Comments

Overall, the paper presents a useful validation effort between GOSAT and aircraft measurements. However, the paper makes almost no mention of TCCON, which serves as the foundation of XCO2 validation for GOSAT by almost all research groups. This paper needs to address the pros and cons of aircraft-based validation vs. TCCON validation. To me, the advantage seems primarily to be the increased number of locations, though many of the aircraft sites have few actual profiles against which to compare. The authors should also compare their results to those of Oshchepkov et al. (2012, hereafter Osh12), which compared NIES v02.00 to TCCON. For instance, Osh12 find a mean bias of -1.93 ppm of GOSAT-TCCON at Lamont (SGP), and a scatter of 1.13 ppm. In this work, you find an even lower bias of -2.6 ppm and a significantly higher scatter of ~ 1.7-1.9 ppm. This implies that the aircraft validation is inherently more uncertain than the TCCON-based validation.

We believe the paper you mentioned must be Oshchepkov et al. (2013, JGR) not Oshchepkov et al. (2012). Oshchepkov et al. (2013) compared the TCCON data to GOSAT data within 5° radius of each TCCON site during June 2009 to March 2011. On the other hand, we performed a comparison of aircraft-based data and GOSAT data retrieved within ±2° or ±5° latitude/longitude boxes centered at each aircraft measurement site during June 2009 to July 2010. This means that the coincidence criteria and analysis period of Oshchepkov et al. (2013) are different from those of our study. In addition, the data processing software of TCCON data that Oshchepkov et al. (2013) used was GGG2009, not the latest version. According to TCCON wiki (https://tccon-wiki.caltech.edu/), the latest version (GGG2012) of TCCON seems to become approximately 0.5 ppm higher than GGG2009. An analysis by Yoshida et al. (2013) followed the descriptions of TCCON wiki, examining TCCON data processed by GGG2009 and GGG2012. If the GGG2012 TCCON data were analyzed by Oshchepkov et al. (2013), the GOSAT bias at SGP would be about -2.43 ppm. So, we think that there is little disparity between their result and ours (-2.66 ppm at SGP).

Based on your suggestions, we cited the previous studies on comparison between GOSAT data and TCCON data (Oshchepkov et al., 2013; Yoshida et al., 2013), and added the following sentences in Sect. 1.

"Along with the TCCON data, aircraft measurement data are useful for the validation of the satellite data. Araki et al. (2010) showed that the uncertainty of XCO_2 over Tsukuba calculated using aircraft data at one aircraft measurement site of Narita was estimated to be ~1 ppm and calculating XCO_2 from airliners could be applied to the validation of GOSAT products. In addition, Miyamoto et al. (2013) provided a method to calculate XCO_2 based on aircraft measurement vertical data (hereinafter aircraft-based XCO_2) at various locations over the world. In this study, we validated Ver. 02.00 of the GOSAT SWIR XCO_2 (released in June 2012) with the aircraft-based XCO_2 calculated using the method as in Miyamoto et al. (2013)."

Added references

Oshchepkov, S., Bril, A., Yokota, T., Wennberg, P. O., Deutscher, N. M., Wunch, D., Toon, G. C., Yoshida, Y., O'Dell, C. W., Crisp, D., Miller, C. E., Frankenberg, C., Butz, A., Aben, I., Guerlet, S., Hasekamp, O., Boesch, H., Cogan, A., Parker, R., Griffith, D., Macatangay, R., Notholt, J., Sussmann, R., Rettinger, M., Sherlock, V., Robinson, J., Kyrö, E., Heikkinen, P., Feist, D. G., Morino, I., Kadygrov, N., Belikov, D., Maksyutov, S., Matsunaga, T., Uchino, O., and Watanabe, H.: Effects of atmospheric light scattering on spectroscopic observations of greenhouse gases from space. Part 2: Algorithm intercomparison in the GOSAT data processing for CO_2 retrievals over TCCON sites, J. Geophys. Res., 118, 1-20, doi:10.1002/jgrd.50146, 2013.

This leads to my second point, that a detailed error analysis is required. The authors cover errors due to the stratospheric CO2 model, the model from the surface to the lowest aircraft measurement, due to the averaging kernel (CAK), and other sources. I suggest they do a real error analysis and attempt to combine all these error sources into a total error that contains all the individual uncertainties. Also, some uncertainty sources are not listed, such as due to the height of the boundary layer and tropopause. And many, many aircraft sites lack tower data. At the sites with tower data, it seems that there can be a large change of CO2 concentration in the PBL. How large an uncertainty is introduced for sites that lack tower data? Finally, are the resulting total uncertainties on the aircraft XCO2 very small (a few tenths of a ppm), or significantly larger (approaching 1 ppm)? Why are the 1-sigma standard deviations for the aircraft significantly larger than for TCCON?

The total uncertainty, based on division of atmospheric layer from the surface to 85 km, was defined by Miyamoto et al. (2013). Miyamoto et al. (2013) defined and determined the uncertainty of partial XCO_2 in four domains: (I) inside the PBL, (II) region above the PBL with observed data, (III) troposphere above the PBL without observed data, and (IV) stratosphere without observed data. We show their results in Table R1-1 (the same as Table 2 of Miyamoto et al., 2013). Based on uncertainties of those partial XCO_2, Miyamoto et al. (2013) calculated the total uncertainty, and in this study, we made GOSAT XCO_2 validation using only aircraft-based XCO_2 data with the total uncertainty of less than 1 ppm. On the other hand, we show the uncertainties of aircraft-based XCO_2 calculation from various factors over Narita in Table R1-2. We here consider uncertainty sources of each domain, comparing Table R1-1 with Table R1-2.

We evaluated the uncertainties of XCO_2 with and without the tower data by comparison of "XCO_2 from both aircraft profiles and tower data (aircraft-tower XCO_2)" and "XCO_2 from only aircraft profiles (aircraft only XCO_2)" in Narita. An average of the difference between aircraft-tower XCO_2 and aircraft only XCO_2 was 0.21±0.75 ppm. The uncertainties of aircraft-based XCO_2 with and without the tower measurements over Narita seem to be a part of the uncertainty (2.89 ppm) of domain I (With observed data in PBL) in Table R1-1. In addition, we calculated the differences between "XCO_2 where PBL heights are true values (PBL_{true} XCO_2)" and "XCO_2 where they are assumed to be 200 m lower than true values ($PBL_{minus200}$ XCO_2) or 200 m higher than true values ($PBL_{plus200}$ XCO_2)" at Narita. The differences between PBL_{true} XCO_2 and $PBL_{minus200}$ XCO_2 were evaluated to be less than 0.63 ppm at most, and 0.12±0.22 ppm on average (Table R1-2). The differences between PBL_{true} XCO_2 and $PBL_{plus200}$ XCO_2 were evaluated to be -0.62 ppm at most, and -0.09±0.23 ppm on average. Similarly, we investigated the differences between "XCO_2 where tropopause heights are true values (TRP_{true} XCO_2)" and "XCO_2 where they are assumed to be 1000 m lower than true values ($TRP_{minus1000}$ XCO_2) or 1000 m higher than true values ($TRP_{plus1000}$ XCO_2)" at Narita (Table R1-2).

In Sect. 4.2, we evaluated uncertainties of XCO_2 by comparing aircraft-based XCO_2 using ACTM, GOSAT a priori profile, and TCCON a prior profile as stratospheric and mesospheric profiles. The differences among them over Narita (-0.24 ppm or 0.30 ppm at most, and -0.12±0.08 ppm or 0.04±0.08 ppm on averages) were less than the standard deviation (1.73 ppm) of domain IV (stratosphere without observed data) in Table R1-1. Consequently, there could be the aircraft-based XCO_2 data with the total uncertainty, which includes uncertainties due to the PBL heights and the tropopause heights and so on, larger than 1 ppm.

TCCON data were used as time-averaged data (e.g. averages of the data obtained within ±30 min) for the GOSAT validation. On the other hand, aircraft measurement data were momentarily obtained at respective heights. We are aware of the fact that the one standard deviation of temporally-averaged TCCON data is smaller than that calculated from aircraft profile data.

Table R1-1. The assumed standard deviations of partial XCO_2 in each domain shown by Miyamoto et al. (2013).

	Standard deviation [ppm]
I (No observed data in PBL)	15
I (With observed data in PBL)	2.89
II	0.4
III	1.73
IV	1.73

Table R1-2.The uncertainties of aircraft-based XCO_2 calculation from various factors over Narita estimated by Miyamoto et al. (2013), this work, and additional analyses.

	average [ppm]	1σ [ppm]	maximum [ppm]	minimum [ppm]
PBL height (PBL_{true} XCO_2/$PBL_{plus\ 200}$ XCO_2)	-0.09	0.23	0.09	-0.62
PBL height (PBL_{true} XCO_2/$PBL_{minus\ 200}$ XCO_2)	0.12	0.22	0.63	-0.03
tropopause height (TRP_{true} XCO_2/$TRP_{plus\ 1000}$ XCO_2)	-0.03	0.06	0.22	-0.30
tropopause height (TRP_{true} XCO_2/$TRP_{minus\ 1000}$ XCO_2)	0.01	0.05	0.25	-0.15
with CAK/without CAK	-0.03	0.10	-0.03	0.10
Dry air number density (CIRA/GPV+CIRA)	0.00	0.04	0.00	0.04
profiles above the tropopause (ACTM/TCCON prior)	-0.12	0.08	0.16	-0.24
profiles above the tropopause (ACTM/GOSAT prior)	0.04	0.08	0.30	-0.16

The authors spend a lot of time discussion the averaging kernel effect only to find that it is small (sections 3.1.4 and 4.1). This was known from previous TCCON-based comparions (for example, Wunch et al. 2011). I suggest that section 4.1 be trimmed for brevity, and the details moved into the supporting materials. It is much too long as it stands just to report that the CAK- – - effect is small (we already knew this was true for TCCON; they've confirmed it for aircraft.)

Thank you for your advice. Surely, Wunch et al (2011) showed CAK effects, but only at Lamont sites. In our study, the CAK effects at various regions of the world were shown. We think it is worth showing those effects. However, we deleted some figures and descriptions on CAK (approximately half of previous manuscript) in Sect. 4.1.

Finally, I recommend that the authors try to be more quantitative in their conclusions. As written, we have learned very little from this aircraft validation effort that we didn't already know from TCCON (as expressed in Osh12). A low bias of "1-2 ppm" and scatter of "1-3" ppm is a huge range.

We think that our validation results by aircraft measurements were almost the same as those by TCCON. Additionally, we showed the results at much observation sites than those by TCCON. As your comment, however, this sentence in Abstract was modified as follows.

(p3204, line21 of ACPD)
"Both methods indicated that GOSAT XCO_2 agreed well with aircraft-based XCO_2, except that the former is negatively biased by 1 – 2 ppm, with a standard deviation of 1 – 3 ppm."
--->
(p2, line20 of revised manuscript)
"The results indicated that GOSAT XCO_2 over land regions agreed with aircraft-based XCO_2, except that the former is biased by -0.68 ppm (-0.99 ppm) with a standard deviation of 2.56 ppm (2.51 ppm), whereas the averages of the differences between the GOSAT XCO_2 over ocean and the aircraft-based XCO_2 were -1.82 ppm (-2.27 ppm) with a standard deviation of 1.04 ppm (1.79 ppm) for ±2-degree (±5-degree) boxes."

Specific Comments

1. In the Introduction, you need to state how this paper is related to Miyamoto et al. (2012). They same to make use of much of the same data.

Thank you for your nice suggestion. We added some descriptions in Sect. 1 as follows.

(p5, line8 of revised manuscript)

"Along with the TCCON data, aircraft measurement data are useful for the validation of the satellite data. Araki et al. (2010) showed that the uncertainty of XCO_2 over Tsukuba calculated using aircraft data at one aircraft measurement site of Narita was estimated to be ~1 ppm and calculating XCO_2 from airliners could be applied to the validation of GOSAT products. In addition, Miyamoto et al. (2013) provided a method to calculate XCO_2 based on aircraft measurement vertical data (hereinafter aircraft-based XCO_2) at various locations over the world. In this study, we validated Ver. 02.00 of the GOSAT SWIR XCO_2 (released in June 2012) with the aircraft-based XCO_2 calculated using the method as in Miyamoto et al. (2013)."

2. Section 3.1.1 concerning the extrapolation of aircraft data to the surface. How did this work, and what kind of uncertainty does it introduce?

We performed the extrapolation of observational data to the surface, assuming that PBL is well-mixed atmospheric layer. The uncertainty from near the surface becomes large when CO_2 concentration becomes extremely high or low near the surface due to air masses coming from urban areas and the presence of source or sink for CO_2 around the site. As shown above, we calculated "XCO_2 from both aircraft profiles and tower data (aircraft-tower XCO_2)" and "XCO_2 from only aircraft profiles (aircraft only XCO_2)" at NRT. An average of the difference between aircraft-tower XCO_2 and aircraft only XCO_2 was 0.209±0.747 ppm. This result follows that of Miyamoto et al. (2013).

3. I suggest combining sections 3.1.2 and 4.2, as both are about the same thing: uncertainty due to the stratospheric & mesospheric CO2 profile. The same actually goes for 3.1.4 and 4.1 (CAK effect). This is more up to the authors but I think combing makes sense.

We moved all results on curve fitting method in Sect. 4 to Supplementary materials. Considering that we delete the curve fitting section (Sect. 4.3.2 in ACPD), Sect. 4 will be extremely short if combining Sect. 3 and Sect. 4. Therefore, we prefer to keep up as it is in terms of balance Sect. 3 and Sect. 4.

4. The paper is rife with statements about biases such as "In ocean regions, GOSAT data were underestimated by 1.64 ± 1.05 ppm". The second number (the standard deviation) implies an uncertainty on the first (the mean difference). This is not the case; in gaussian statistics, the uncertainty on the mean is the standard deviation divided by the sqrt of the number of observations. However, that is only the case in which the errors are uncorrelated, which is usually a bad assumption when it comes to XCO2. I suggest breaking these statements up into something like: "In ocean regions, the mean bias of GOSAT relative to aircraft was 1.64 ppm, with a standard deviation between the two datasets of 1.05 ppm." Also, some of these statements can be removed and the user directed to tables.

As you suggested, we revised these sentences as follows.

(p3219, line13 of ACPD)
"In ocean regions, GOSAT data were underestimated by 1.64 ± 1.05 ppm and 2.29 ± 1.84 ppm for the ±2-degree and ±5-degree boxes, respectively, compared to reference data."
--->
(p19, line16 of revised manuscript)
"In ocean regions, the mean biases of GOSAT data relative to aircraft measurements were -1.82 ppm with a standard deviation between two datasets of 1.04 ppm and -2.27 ppm with a standard deviation between two datasets of 1.79 ppm for the ±2-degree boxes and ±5-degree boxes, respectively."

(p3219, line17 of ACPD)
"Over the land regions, GOSAT SWIR XCO_2 had a low bias of 0.75 ± 2.57 ppm and 1.01 ± 2.51 ppm and the correlation coefficients were 0.85 and 0.86 with significance at the 99% level for the ±2-degree and ±5-degree boxes, respectively."
--->
(p19, line21 of revised manuscript)
"Over the land regions, the mean biases of GOSAT SWIR XCO_2 relative to aircraft measurements were -0.68 ppm with a standard deviation between two datasets of 2.56 ppm and -0.99 ppm with a standard deviation of 2.51 ppm, and the correlation coefficients were 0.85 and 0.86 with significance at the 99% level for the ±2-degree and ±5-degree boxes, respectively."

5. In the curve fitting method (section 4.3.2), I note that the equation cannot handle interannual

differences in the seasonal uptake. It has been posited that throughout the northern hemisphere, seasonal land uptake was less in 2010 than in 2009; this is clearly visible in the author's SM plots. This will lead to additional errors in this approach. The authors need to state this. Further, it would be very helpful to see the standard devation of the curve fit - observation data for each of the plots in the SM - could the authors put this somewhere, and state in 4.3.2 what was the typical error in the fit itself (in terms of actually fitting the observations)?

Thank you very much for your nice suggestion. At first, we moved all descriptions on curve fitting analysis to Supplementary materials. We added the following sentences in the Supplementary materials.

(p1, the start of the second paragraph of the Supplementary materials)
"Before the validation, we focus on the uncertainties of aircraft-based XCO_2 arisen from the curve fitting. It is considered that there are significant interannual differences of CO_2 uptake during the Northern Hemisphere summer between 2009 and 2010 (e.g. Guerlet et al., 2013). Our estimation does not consider the interannual differences in the seasonal uptake of CO_2, so this may lead to an error source in this curve fitting approach."

Then, we defined the 1 standard deviations of the differences between "true aircraft-based XCO_2 values" and "the calculated values (i.e. estimates) in observation time of the respective XCO_2 data by curve fitting" as uncertainties due to the curve fitting method. The 1 standard deviations of the differences at each aircraft site are listed in Table S-1 of the Supplementary materials. We added the following descriptions.

(p1, the sixth sentence of the second paragraph of the Supplementary materials)
"In this study, the uncertainties due to the curve fitting method are defined and calculated We defined 1σ of the differences between "true aircraft-based XCO_2 values" and "the calculated values (estimates) in aircraft measurement time of the respective XCO_2 data by curve fitting" as uncertainties due to the curve fitting method. Table S-1 summarizes 1σ of the differences at each aircraft site. The uncertainties are about or less than 1 ppm, except two sites (SRG and BNE)."

6. Section 4.3.1, statement about difference between land & ocean biases does not actually hold for the curve fit results. I therefore recommend removing this, or saying that in the curve-fit

results, the land-ocean differences were about the same (table 5).

Because results of curve fitting method were moved to the Supplementary materials, we like to keep those descriptions.

7. Section 4.3.1, last sentence. What does "agreed" mean here? You need to be specific! Agreed to within 3ppm is not exactly a great success story when accuracies significantly better than 1ppm are required to improve carbon cycle science.

We agree with you for the most part. We would like to emphasize that our results show the steady progress is being made in the field of satellite remote sensing though less accurate than in-situ measurements. The last sentence of Sect. 4 was revised as follows.

(p3220, line7 of ACPD)
"In addition, the present version (Ver. 02.00) of GOSAT XCO_2 observed over both land and ocean regions agreed with aircraft measurement data."
--->
(p20, line16 of revised manuscript)
"The GOSAT XCO_2 data (Ver. 02.00) observed over not only land but also ocean regions are significantly correlated with aircraft measurement data."