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.

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 #2

Dear authors, dear editor,

please excuse the delay. This was not an easy task.

The manuscript by M. Inoue et al. describes an intercomparison of the GOSAT XCO2 data product (Ver 02.00) with airborne and CO2 measurements that have been augmented with tower in-situ measurements in some locations. The effects of including or neglecting the influence of the GOSAT column averaging kernels (CAK) as well as the missing stratospheric and mesospheric CO2 in the aircraft profiles on these intercomparisons are discussed in detail. Due to a lack of direct matches between satellite overpasses and aircraft measurements, the authors also try to interpolate aircraft XCO2 estimates in time to compare with GOSAT XCO2 retrievals.

1 Major issues

• As an attempt to truly validate the GOSAT XCO2 data product (Ver 02.00) the methods are not adequate. A validation effort for a dataset should try to use different methods to compare the data being validated against other data sets to establish credibility and define error bars. This manuscript only provides a mere intercomparison of the GOSAT retrievals with airborne in-situ measurements. Thus, the title should not be "Validation of . . . " but rather "Comparison of

. . . ". From a real validation paper I would expect more, for example comparison to other obvious reference data sets like the ground based FTIR measurements from the Total Carbon Column Observing Network (TCCON) or other satellite measurements. In the current form, I can only assume that at some later time, there will be a GOSAT XCO2 (Ver 02.00) vs. TCCON comparison and possibly comparisons against other data sets. However, this would only provide individual biases and error bars. Instead, a consistent data quality assessment using several valdiation sources would be much more useful for the new GOSAT XCO2 (Ver 02.00) data product.

As you commented, we should have reviewed the previous validation studies using TCCON data. Firstly, we added descriptions on the previous studies of the GOSAT (V02.xx) validation using TCCON data (Yoshida et al., 2013; Oshchepkov et al., 2013) in Sect. 1. Please see our reply (p6-7) on 2 Minor issues you mentioned for the details. However, TCCON sites are concentrated mainly in Europe, North America, and Oceania. Our analyses by aircraft measurements showed the results at much number of observation sites in a larger area than those by TCCON.

We compared aircraft data with TCCON data. Aircraft-based XCO_2 at Narita (NRT), Sydney (SYD), Park Falls (LEF), and the Southern Great Plains (SGP) was compared with TCCON XCO_2 at Tsukuba, Wollongong, Park Falls, and Lamont, respectively. TCCON XCO_2 data were averaged within ±30 minutes of GOSAT overpass time because they were originally prepared for validation of the GOSAT products. Then, aircraft-based XCO_2 data at each site were compared with TCCON XCO_2 on the same day as aircraft measurement. Figure R2-1 shows the scatter diagram of TCCON XCO_2 and aircraft-based XCO_2 at 4 sites. The averages of the differences (aircraft minus TCCON) and the 1 standard deviations were 0.00 ± 1.10 ppm at NRT and -0.61 ± 1.27 ppm at LEF (Table R2-1). The correlation coefficient and average of the differences at all sites are 0.94 (with statistical significance at the 99% level) and -0.08 ± 1.09 ppm, respectively. Thus, we found that aircraft-based XCO_2 data at several observation sites were in good agreement with co-located TCCON data. This result is very interesting and we think we would submit this as a separated paper.

In addition, 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 1 standard deviation of temporally-smoothed TCCON data is smaller than that of aircraft measure data. Furthermore, in this paper, we made GOSAT validation using

"only aircraft-based XCO₂ data with an uncertainty (based on Miyamoto et al., 2013) of less than 1ppm". We conclude that XCO₂ data from aircraft measurement are useful for the validation of the GOSAT data, though less accurate than TCCON data.
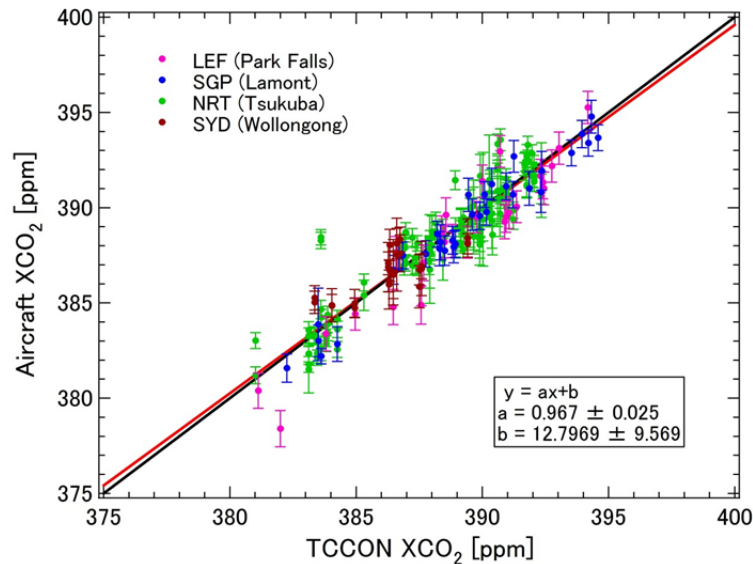

Figure R2-1. Scatter diagram between aircraft-based XCO₂ and TCCON XCO₂ on the same day as aircraft measurement at each site. Red line denotes the regression line based on all data. The one-to-one line is plotted as a black line.

Table R2-1. The average, maximum, minimum, and 1 standard deviation of differences of aircraft-based XCO₂ and TCCON XCO₂ at each observation site.

	LEF (Park Falls)	SGP (Lamont)	NRT (Tsukuba)	SYD (Wollongong)	All sites
Number of dataset	27	33	132	24	216
R	0.95	0.98	0.93	0.77	0.94
average [ppm]	-0.609	-0.215	0.003	0.287	-0.075
1σ [ppm]	1.267	0.745	1.100	1.014	1.087
maximum [ppm]	2.251	1.443	4.829	1.908	4.829
minimum [ppm]	-3.606	-1.500	-1.864	-1.652	-3.606

• The aircraft measurements that were used are certainly not everything that was available during the GOSAT era. Namely, aircraft CO_2 measurements from various campaigns like

BARCA (Chen et al., 2010), the TCCON calibration campaigns (Wunch et al., 2010; Messerschmidt et al., 2011), or the various HIPPO campaigns (Wofsy, 2010) were not used. There are also regular low-altitude aircraft measurements at the Bialystok tall-tower site (Messerschmidt et al., 2012) and possibly other tall-tower sites in Europe that were part of the CarboEurope project. I understand that there might not have been enough overlap with these measurements and GOSAT retrievals but that should at least be mentioned.

We added results of comparisons between GOSAT XCO_2 and aircraft-based XCO_2 calculated from the HIPPO programme and the GOSAT validation aircraft observation campaign by NIES and JAXA in this manuscript. We also investigated data obtained from the TCCON calibration campaign in Europe. Unfortunately, there were no data temporally matched up with the GOSAT data at European sites. Because an observational altitude of regular aircraft measurements at the Bialystok site is restricted to about 3 km, it is very difficult to calculate XCO_2 without large uncertainties.
We added the following sentences in Sect. 2.2.
(p9, line3 of revised manuscript)
"There are other regular aircraft measurements or campaigns over the world. We also investigated data obtained from the TCCON calibration campaign in Europe (Wunch et al., 2010; Messerschmidt et al., 2011). Unfortunately, there were no data temporally matched up with the GOSAT data at European sites. Additionally, an observational altitude of regular aircraft measurements at the Bialystok site is restricted to about 3 km (Messerschmidt et al., 2012). Since it is very difficult to calculate XCO_2 without large uncertainties, CO_2 profiles at Bialystok were not used in this study."

• I am not happy with the curve fitting method that has been employed to extend the number of available comparison points. Though I understand that the number of direct GOSAT/aircraft matches was too low for a meaningful comparison, I do not think that this is a valid approach – at least not in the form it was done here. One issue that should definitely be addressed is the error contribution that results from this interpolation. This could have been estimated by comparing measured and interpolated XCO2 values to datasets generated by transport models like Carbontracker. This way one would get a feeling for the expected interpolation errors. An even better way would have been to use a well-known data product like Carbontracker to provide interpolated values in the first place.

We moved all results on curve fitting method in Sect. 4 to Supplementary materials. Here, 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. The results showed that uncertainties due to the curve fitting method were about 1 ppm at many sites, but over 2 ppm at two sites. We think it is interesting that comparing aircraft-based XCO_2 values to Carbontracker. We would like to conduct using CarbonTracker as a future work.

In its current form of a mere intercomparison, the manuscript is rather technical and would be better suited for publication in AMT. For ACP, I would suggest major revisions as described above.

2 Minor issues
• p. 3204, l. 21–23: I am not sure if "agree well" is appropriate with a standard deviation of 1–3 ppm and a bias of 1–2 ppm. This is certainly a big improvement since the previous GOSAT XCO2 product but still quite a lot.

We revised this sentence 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."
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(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."

• p. 3204, l. 4: You should also mention the tower measurements.

We added the following sentence in Abstract.
(p2, line9 of revised manuscript)
"To calculate XCO_2 based on aircraft measurements (aircraft-based XCO_2), tower

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measurements and model outputs were used for additional information near the surface and above the tropopause, respectively."

• p. 3204, l. 11: ±0.1 ppm
• p. 3205, l. 21: ±1%

We corrected them.

• p. 3205, l. 28: In-situ measurements are not the only form of validation data.

We revised the description you mentioned as follows.
(p3205, line25 of ACPD)
"Therefore, satellite-based data products must be validated by higher-precision data obtained independently using atmospheric measurements at the Earth's surface or on board the aircraft."
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(p4, line4 of revised manuscript)
"Therefore, satellite-based data products must be validated by higher-precision data obtained independently such as ground-based Fourier Transform Spectrometer (FTS) data and aircraft measurement data."

• p. 3206, l. 1–16: The introduction is too detailed and too lenghty. It could be cut by about one third. This part would be a good start.

As you suggested, we shortened and reorganized Sect. 1 Introduction. We hope that new Sect. 1 looks better.

• p. 3206, l. 28: Let us know why you are ignoring TCCON data.

We revised a part of Sect. 1 by adding descriptions on the validation of the GOSAT using TCCON data (Yoshida et al., 2013; Oshchepkov et al., 2013) as follows.

(p3206, line17 of ACPD)
"More recently, the Greenhouse gases Observing SATellite "IBUKI" (GOSAT), the world's first satellite dedicated to measuring the atmospheric concentrations of CO_2 and CH_4 from

space, has been operated since the early 2009 and the preliminary results have been published by the National Institute for Environmental Studies (NIES) GOSAT project team (Yokota et al., 2009; Yoshida et al., 2011; Morino et al., 2011). Yoshida et al. (2011) presented global distributions of XCO_2 and column-averaged volume mixing ratios of methane (XCH_4) retrieved from the Short-Wavelength InfraRed (SWIR) spectra of the Thermal And Near-infrared Sensor for carbon Observation - Fourier Transform Spectrometer (TANSO-FTS) onboard the GOSAT. Morino et al. (2011) performed the preliminary validation of GOSAT SWIR XCO_2 and XCH_4 (Ver. 01.xx, earlier version released in August 2010) using data provided by a worldwide network of ground-based FTS called the Total Carbon Column Observing Network (TCCON; Wunch et al., 2011). The results indicated that Ver. 01.xx of the GOSAT SWIR XCO_2 was biased by 8.85 ± 4.75 ppm (2.3% ± 1.2%) lower than the reference values.

In this study, Ver. 02.00 of the GOSAT SWIR XCO_2 (released in June 2012) was validated using aircraft measurement vertical data."

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(p4, line20 of revised manuscript)

"More recently, the Greenhouse gases Observing SATellite (GOSAT), the world's first satellite dedicated to measuring the atmospheric concentrations of CO_2 and CH_4 from space, has been operated since the early 2009 and the observational results have been reported (Yokota et al., 2009; Yoshida et al., 2011; Morino et al., 2011; Oshchepkov et al., 2013). Yoshida et al. (2013) presented global distributions of XCO_2 retrieved from the Short-Wavelength InfraRed (SWIR) spectra of the Thermal And Near-infrared Sensor for carbon Observation - Fourier Transform Spectrometer (TANSO-FTS) onboard the GOSAT. In addition, they performed the validation of GOSAT SWIR XCO_2 (Ver. 02.xx, latest version released in June 2012) with data provided by a worldwide network of ground-based FTS called the Total Carbon Column Observing Network (TCCON; Wunch et al., 2011) and showed that the mean bias of the GOSAT XCO_2 (Ver. 02.xx) was -1.48 ppm with a standard deviation of 2.09 ppm.

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 with the aircraft-based XCO_2 calculated using the method as in Miyamoto et al. (2013)."

• p. 3207, l. 6–22: This part does not really belong in the introduction.

• p. 3207, l. 7-9: First the authors tell us that aircraft profiles have to be convoluted with the CAK, then they tell us that this is not necessary. This needs to be better explained. This might be resolved by moving this part out of the introduction (e.g. into Section 3).

Based on your two comments, we moved discussions on CAK of Sect. 1 Introduction to Sect. 3. The following sentences were added in the last paragraph of Sect. 3.1.4. This means that we cannot apply GOSAT CAK to the fitted aircraft-based XCO_2 due to the absence of the vertical information for in-situ measurements when comparing with curve fitting method. (We can apply GOSAT CAK to aircraft-based XCO_2 when directly comparing GOSAT data with temporally matched aircraft data.) We hope the revised descriptions look better.

(p14, line16 of revised manuscript)
"It is necessary to apply the GOSAT SWIR CAK and convolution with the a priori profiles used in satellite data retrievals to the aircraft measurement data for a meaningful comparison between the two measurements. We applied the GOSAT CAK to aircraft-based XCO_2 calculation when comparing the GOSAT data with temporally matched aircraft data (Sect. 4.3). On the other hand, we cannot apply the GOSAT SWIR CAK to the fitted aircraft-based XCO_2 due to the absence of the vertical information for all aircraft measurements when comparing of GOSAT SWIR XCO_2 with the gap-filling time series of the aircraft-based XCO_2 through curve fitting (see the Supplementary materials for details on comparisons by curve fitting method). Therefore, we first evaluated the impact of GOSAT SWIR CAK on the aircraft-based XCO_2 calculation (Sect. 4.1)."

• p. 3208, l. 1–18: Again, this is very lengthy.

We shortened a part of Sect. 2.1 (on overview of GOSAT) as follows.

(p3208, line4 of ACPD)
"GOSAT was launched on 23 January 2009 from the Japan Aerospace Exploration Agency (JAXA) Tanegashima Space Center in Japan and has been operational since April 2009. GOSAT flies at an altitude of approximately 666 km and completes one revolution in about 100 minutes. The satellite returns to the same point in space in 3 days making global observations of several tens of thousands of ground points by TANSO-FTS. TANSO-FTS has three SWIR spectral bands centered at 0.76, 1.6, and 2.0 μm and one broad TIR band

between 5.6 and 14.3 μm. XCO_2 and CO_2 concentration profile can be retrieved from SWIR and TIR bands, respectively (Saitoh et al., 2009; Yoshida et al., 2011). This study focuses on validation of XCO_2 retrieved from SWIR spectra by the latest retrieval algorithm (Ver. 02.xx; Yoshida et al., in preparation). From all SWIR spectra observed with TANSO-FTS, the cloud-free measurements with solar zenith angle less than 70 degrees and signal-to-noise ratio (SNR) larger than 70 for O_2 sub-band (12950 − 13200 cm-1) are selected and used to retrieve XCO_2. After the quality check for the retrieved results, the typical range of the XCO_2 a posteriori error is 0.8 − 1.4 ppm with its mode value of 0.9 ppm."

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(p6, line4 of revised manuscript)
"GOSAT is a satellite for spectroscopic remote sensing of the greenhouse gases that was launched on 23 January 2009 (Kuze et al., 2009). TANSO-FTS onboard GOSAT has three bands in the SWIR region centered at 0.76, 1.6, and 2.0 μm and one broad thermal infrared (TIR) band between 5.6 and 14.3 μm. The measurements in SWIR and TIR bands allow for the retrievals of XCO_2 and CO_2 concentration profiles, respectively (Saitoh et al., 2009; Yoshida et al., 2011, 2013). In this study, we performed the validation of XCO_2 retrieved from SWIR spectra with the latest retrieval algorithm (Ver. 02.xx; see Yoshida et al., 2013 for details)."

• p. 3210, l. 5–7: Explain why you have not used any of the other available aircraft measurements.

As noted above, we added results of the HIPPO programme and GOSAT validation aircraft observation campaign by NIES and JAXA. Though we tried to add the TCCON calibration campaign data in Europe, there were no data temporally matched up with the GOSAT data.

• p. 3210, l. 16: There are more tower measurements available word-wide than the ones you have used. Explain why these were not considered.

The theme of this paper is validation of GOSAT data using aircraft measurements. As you commented, there are more other tower measurement sites over the world. However, we needed to use CO_2 data obtained at sites where there are both aircraft and tower measurements at about the same time to calculate aircraft-based XCO_2 including tower data. For instance, there are some tower sites (e.g. Walnut Grove, WGC) we could not use the tower data due to absence of aircraft data during the analysis period of this study.

• p. 3210, l. 25–27: As mentioned above, there are also aircraft and tall-tower measurements at the TCCON station at Bialystok, Poland. Please explain why these have not been used.

Because an observational altitude of regular aircraft measurements at the Bialystok site is restricted to about 3 km, it is very difficult to calculate XCO₂ without large uncertainties.

• p. 3214, l. 2: A figure showing the shape of the CAK with respect to SZA would be useful.

Examples of CAK for GOSAT XCO₂ at seven different solar zenith angles (every 10 deg. between 10-70 deg.) are shown in Fig. R2-2. Thus, we find that the shapes of CAK above the middle troposphere vary due to different solar zenith angles. However, we are afraid that this figure and description may cause distraction in the current form of manuscript, and decided not to add this figure in text.
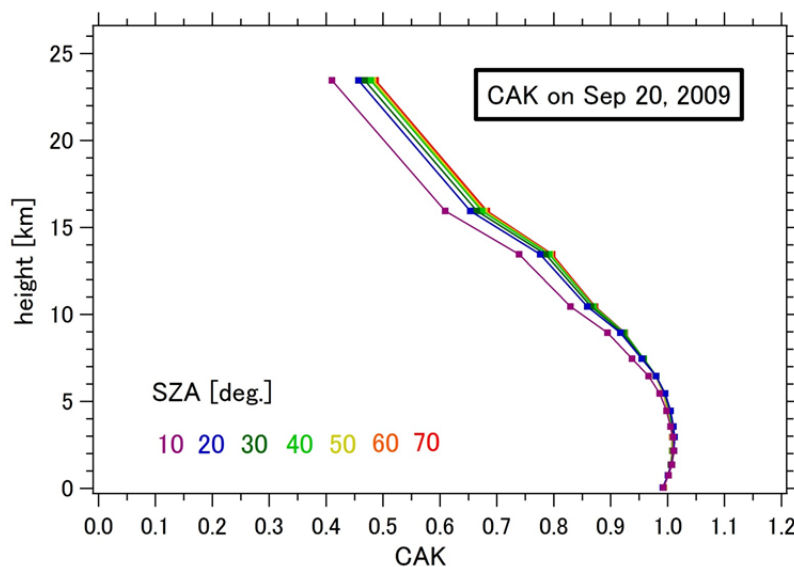

Fig. R2-2. Examples of CAKs for GOSAT XCO₂ on 20 September, 2009. The shapes of CAKs at seven different solar zenith angles are shown by color.

• p. 3214, l. 9: Should read: "GOSAT a priori profiles have some effects : : :" (not "make").

We revised this sentence in Sect. 3.1.4 as follows.

(p3214, line9 of ACPD)

"GOSAT a priori profiles make some effects on XCO_2 retrieval."

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(p14, line6 of revised manuscript)

"GOSAT a priori profiles have some effects on XCO_2 retrieval."

• p. 3215, l. 24: ±10° is a huge area!

Based on your comment, we investigated CAK effects using the GOSAT data obtained within ±5° latitude/longitude boxes centered at the aircraft sites, and compared a result in case of ±5° boxes with that of ±10° boxes. As shown in Table R2-2, both results are almost the same. The number of sites used in case of ±10° boxes was 41 of all 47 sites, whereas the number of sites used in ±5° boxes was 34. As one of our aims in this study was to investigate the CAK effects at various sites, we decided to show the results of ±10° boxes. We added or revised some descriptions as follows.

(p3215, line22 of ACPD)

"We made a connection between aircraft-based data at certain time of the day and the GOSAT data nearest to the aircraft observation site for all GOSAT data obtained within ±10° latitude/longitude boxes centered at the observation site on the same day."

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(p16, line4 of revised manuscript)

"We made a connection between aircraft-based data at certain time of the day and the GOSAT data nearest to the aircraft observation site for all GOSAT data obtained within ±10° latitude/longitude boxes centered at the observation site on the same day. When we use the ±5-degree boxes, the number of unavailable observation site becomes over 10, and the results for available sites are almost same as those for the ±10-degree boxes (results for the ±5-degree boxes are not shown)."

Table R2-2. The average, maximum, minimum, and 1 standard deviation (1σ) of the differences between aircraft-based XCO₂ with and without the application of GOSAT column averaging kernels at all aircraft sites.

	number of used sites	data number	average [ppm]	1σ [ppm]	maximum [ppm]	minimum [ppm]
±5° boxes	34	222	-0.028	0.081	0.249	-0.360
±10° boxes	41	671	-0.022	0.088	0.252	-0.360

• p. 3219, l. 13–14: Please rewrite the sentence with ": : : were underestimated : : :". It is not clear from that sentence if the GOSAT or reference data were lower.

Based on your and the other referee's suggestions, we revised this sentence as follows. (p3219, line17 of ACPD)

"Over the land regions, GOSAT SWIR XCO₂ 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."

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(p19, line21 of revised manuscript)

"Over the land regions, the mean biases of GOSAT SWIR XCO₂ 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° and ±5° boxes, respectively."

• p. 3220–3221: I have already stated that I find the whole approach too simple. The least that would be necessary would be a figure or a table that shows us how far in space and time the interpolated measurements were from actual GOSAT measurements. If the interpolation only bridges a few hours it might be ok. With days or weeks I would not trust it.

As mentioned above, we moved results on curve fitting method to the Supplementary materials. In curve fitting approach, we compared GOSAT data with interpolated aircraft-based XCO₂ in "the GOSAT overpass time". For example, we compared GOSAT data whose overpass time is UTC 3:53 on June 28, 2009 with interpolated values of aircraft-based XCO₂ at UTC 3:53 on June 28, 2009. That is, the GOSAT overpass time and the time of

interpolated aircraft-based data are same. We added the following sentence in the Supplementary materials as follows.

(p1, the 15th sentence of the first paragraph of the Supplementary materials)
"The GOSAT XCO$_2$ data observed within the ±2° and ±5° latitude/longitude boxes centered at each aircraft measurement site were compared with the calculated aircraft-based XCO$_2$ (i.e. estimates) in the GOSAT overpass time."

Next, we show how far in space it is from aircraft site to the location of GOSAT data used for the curve fitting approach. Figure R2-3 shows the distance from each aircraft site to the GOSAT data obtained within ±5-degree latitude/longitude boxes of each site for all sites (i.e. absolute values of the latitude/longitude differences). We found that the matched data are distributed with uniformity in ±5-degree latitude/longitude boxes.
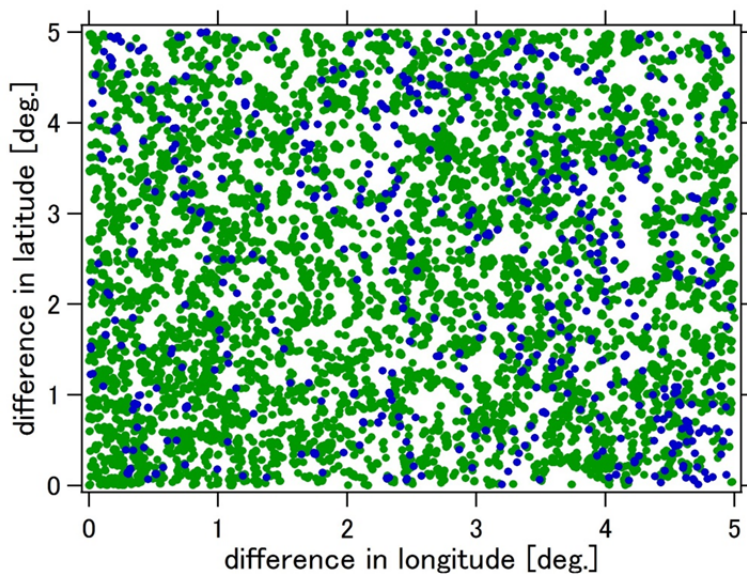

Fig. R2-3. The distance from each aircraft site to the location of GOSAT data obtained within ±5° latitude/longitude boxes of each site (i.e. absolute values of the latitude/longitude differences). Green and blue dots indicate the distance from aircraft site to the location of the GOSAT data retrieved over land and ocean, respectively.

• Table 2: The table does actually not tell anything about the effects of using or not using the

CAK on the aircraft profiles even though the caption says so.

A caption of Table 2 is "The average, maximum, minimum, and 1 standard deviation (1σ) of the differences between aircraft-based XCO₂ with and without the application of GOSAT column averaging kernels at each aircraft observation site." We believe that this caption does not tell anything about the effects of using or not using the CAK on the aircraft profiles. However, we reduced some direct descriptions such as "we investigated the impacts of GOSAT CAK on the aircraft-based XCO₂ calculation" in text.

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