Reply to the comments by Referees

To Associate Editor and Referees,

We appreciate you reading our paper carefully and giving valuable comments and suggestions again. We have considered your recommendations for revisions and made the necessary changes. The major points that we deal with in the revised manuscript are as follows:

1. Following the advice of the Referee #2, we have added Table 1 to show representative pressure levels of each of the retrieval grid layers of GOSAT/TANSO-FTS thermal infrared (TIR) version 1 (V1) Level 2 (L2) CO_2 product. (We have already addressed this in AMTD.)
2. Relating to the above, we have referred to the retrieval grid layers by the representative pressure levels throughout the text. (We have already addressed this in AMTD.)
3. Following the advice of the Referee #1, we have added Table 2 to present bias values of GOSAT/TANSO-FTS TIR V1 L2 CO_2 data against CONTRAIL CME CO_2 data to which TIR CO_2 averaging kernel functions were applied. It could help readers see Figure 6.
4. Following the advice of the Referee #1, we have added Table 3 to present mode values of frequency distributions of differences in monthly averaged CO_2 concentrations between original or bias-corrected TIR and NICAM-TM CO_2 data and numbers of data categorized into the mode values and all 2.5° gridded data used for comparisons. It could help readers see Figure 7.

Individual responses to the Referees' comments are listed below.

Reply to Referee #1,

The paper assesses biases in satellite-retrieved CO_2 concentrations at the lower and middle troposphere from GOSAT/TANSO-FTS TIR V1 product by comparing them with precise aircraft measurements by CONTRAIL CME, followed by global comparisons of bias-corrected CO_2 concentrations with model-simulated CO_2 by NICAM-TM. The authors found that the TIR data had negative biases of 1-1.5% against the aircraft measurements and bias-corrected TIR data showed generally good agreement with the NICAM-TM CO_2 data, which demonstrated the validity of the bias-correction values.

Observational CO_2 data in the free troposphere is still limited, and CO_2 profiles from high-resolution GOSAT TIR spectra will help to elucidate CO_2 variations in the free troposphere with its global coverage. Bias estimation of satellite-based CO_2 products is highly important for data users and further analysis of CO_2 fluxes by atmospheric inversion/data-assimilation studies. The paper is *generally well written, and I recommend accepting it for publication after the comments listed below have been addressed.*

General comments:

1 . Results section: The paper presents comparisons between the original TIR data and CONTRAIL CME data and between bias-corrected TIR data and NICAM-TM data. But the expressions of the evaluations are often qualitative, such as "relatively low", "tend to be larger", "slightly increase", "nearly identical", "close to zero" without any supporting numbers. Although one can see tendencies on the plots, I would recommend illustrating the point with some numbers and add a table with quantitative values to explain the results clearly. The authors do not need to write all related numbers, but at least it would be better to write statistic values related to Figure 7, one of the main plots, to show the validity of the bias-correction values quantitatively. Statistic values in a table or the main text may help readers to follow the discussion. They can be mode values (or medians), standard deviations, kurtoses and skewnesses of frequency distributions, the total number of data pairs, or whatever the authors need to describe Figure 7.

Reply:

We totally agree with you. As described above, we have added Table 2 and Table 3 to present specific values of what we focused on in Figure 6 and Figure 7, respectively. In the revised manuscript, we have referred to Table 2 and Table 3 to clarify points of discussions related to Figure 6 and Figure 7. We have also referred to specific values presented in Table 2 and Table 3 in the main text of the revised manuscript. We appreciate your comment.

2. "East Asia" in abstract and discussion section: The authors conclude that one of the reasons of the overcorrection in JJA/low latitudes (0S-20N)/upper MT region is that the correction values were determined by using the data over East Asian airports. Since the authors write this finding to the abstract, this conclusion is thought to be important for the paper. But the explanation (p.10, L34 - L11, L8) is not clear enough to understand why data in the East Asia region strongly affects to the 0-20N bias correction. Usually, Asia in 20S-20N is called Southeast Asia (or part of South India). Do the authors mean "Southeast Asia" rather than "East Asia"? Or if the East Asian data truly affects the 0-20N bias-correction values via atmospheric transport, please give more explanation and references.

Reply:

We greatly appreciate you pointing out this. We wrote "East Asia" incorrectly in the sentences where we should have written "Southeast Asia" in the manuscript. We intended to say that the bias-correction values in low latitudes (20°S−20°N) in the JJA season in 2010 were determined on the basis of comparisons over the three airports over Southeast Asia: BKK (Bangkok), SIN (Singapore), and CGK (Jakarta). In the revised manuscript, we have replaced "East Asia" with

"Southeast Asia" throughout the text and described these specific airports in the discussion part.

Specific comments:

Page 3, Section 2, TIR data: Does the TIR product include nighttime data as well as daytime data? I suggest writing time of the observations briefly somewhere in this section.

Reply:

The TIR products of GOSAT/TANSO-FTS include data obtained both in daytime and nighttime. Following your suggestion, we have stated this clearly in the revised manuscript as follows:

"The TIR band of TANSO-FTS makes observations both in daytime and nighttime, unlike the SWIR band."

Page 4, Section 3, NICAM-TM data: NICAM-TM inversion with CONTRAIL data was conducted for the period 2006-2008 (Niwa et al., 2012). It should be explained briefly how the 2010-2012 CO_2 data was calculated by NICAM-TM.

Reply:

We agree with you. As you pointed out, the NICAM-TM inversion simulation that was conducted in Niwa et al. (2012) used CONTRAIL and surface CO_2 data in 2006–2008 to estimate the natural flux of CO_2. The NICAM-TM CO_2 data used here were generated by using the estimated CO_2 natural flux (fixed for 2010−2012) and year-dependent CO_2 fluxes from fossil fuel and biomass burning emissions (considering their yearly trends). Following your suggestion, we have added more explanation of the NICAM-TM CO_2 inversion as follows:

"In this study, simulation of NICAM-TM used inter-annually varying flux data of fossil fuel emissions (Andres et al., 2013) and biomass burnings (van der Werf et al., 2010), and the residual natural fluxes from the inversion of Niwa et al. (2012), which mostly represent fluxes from the terrestrial biosphere and oceans. The inversion analysis of Niwa et al. (2012) was performed for 2006−2008 and the three-year-mean fluxes were used in this study."

We appreciate your comment.

Page 5, line 24, "the number of pairs": Could the authors show the number of pairs which finally used for the comparisons for each latitude bands?

Reply:

Following your suggestion, we have described the numbers of coincident pairs of TIR and CME_AK CO_2 profiles for each of the four latitude bands in the fourth paragraph of Chapter 4.1 in the revised manuscript:

"The numbers of coincident pairs of TIR and CME_AK CO_2 profiles varied depending on latitude band and season. The largest number of coincident pairs was obtained in the latitude band of 20°N−40°N including Narita airport, where 506−2501 pairs were obtained. 63−310 and 77−472 coincident pairs were obtained at 40°S−20°S and 40°N−60°N, respectively. The comparison area for low latitudes was extended to a band of 20°S−20°N, because the number of coincident pairs in that region was smaller (0−341) than in other latitude bands; nevertheless, there were no coincident pairs at 20°S−20°N in the JJA seasons of 2011 and 2012. The number of coincident pairs was smallest (0−30) at 20°S−0° and no data were collected there after September 2010. Thus, all bias-correction values for 20°S−20°N after the SON season of 2010 were determined based on data from 0°−20°N."

The below-attached table shows the numbers of the coincident pairs for each season for each latitude band.

		40ºS−20ºS		20ºS−0º/0º−20ºN		20ºN−40ºN		40ºN−60ºN	
2010, MAM	2010, JJA	63	75	27/114	30/95	1305	2501	472	161
2010, SON	2010, DJF	128	114	0/172	6/155	2133	1588	454	132
2011, MAM	2011, JJA	209	183	0/49	0/0	506	1255	77	227
2011, SON	2011, DJF	179	78	0/137	0/234	1529	1049	199	253
2012, MAM	2012, JJA	310	105	0/49	0/0	748	1815	418	406
2012, SON	2012, DJF	145	166	0/31	0/341	2045	1664	326	119

Page 7, line 10, "On a global scale, the seasonality of negative biases was not clear, given the relatively large 1-σ standard deviations, although these biases tended to be larger in the spring hemisphere than in the fall hemisphere.": The sentence is not clear. Does this mean the negative biases had measurable spring-fall seasonality, but it was not statistically significant due to the large standard deviations? Or actually, the biases had no seasonality?

Reply:

In northern middle latitudes (20°N−40°N), negative biases in TIR CO_2 data were larger in spring (MAM) and summer (JJA) than in fall (SON) and winter (DJF). On a global scale from 40°S−60°N, any statistically significant seasonality was not found in negative biases in TIR CO_2 data against CONTRAIL CME_AK CO_2 data. In Table 2 of the revised manuscript, we have presented bias values of TIR CO_2 data against CME_AK CO_2 data in each season at 541−464 hPa and 464−398 hPa (corresponding to layers 5−6) to make readers refer to specific values that we focused on.

Page 7, line 26, "negative biases of TIR CO_2 data against NICAM-TM CO_2 data in all seasons slightly increased over time": Is there no possibility that small trend error in NICAM-TM CO_2 could attribute the bias increase in Fig.7? The NICAM-TM natural fluxes were estimated for the period 2006-2008, which is different from the target period of this article. In other words, does the NICAM CO_2 have no bias in trends against CONTRAIL CME data? The authors can confirm it by plotting NICAM-TM CO_2 data against CONTRAIL CME data like Fig.6.

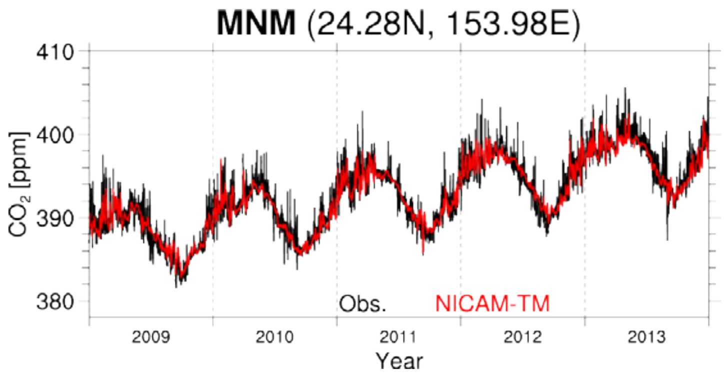
Reply:

As explained above, the NICAM-TM inversion simulation that was conducted in Niwa et al. (2012) used CONTRAIL and surface CO_2 data in 2006–2008 to estimate the natural flux of CO_2. When calculating CO_2 concentrations in 2010–2012, the mean inversion fluxes were cyclically used, but fossil fuel and biomass burning CO_2 fluxes used were varied inter-annually. We confirmed that the growth rate of the calculated NICAM-TM CO_2 concentrations for 2010–2012 is reasonable (2.4 ppm/yr) judging from an observation-based growth rate (2.2 ppm/yr), which is partly contributed by the fact that there were no major El Nino events for both the periods. The below-attached figure shows comparison between the NICAM-TM CO_2 simulations and observations at the surface station at Minamitorishima, which demonstrates the validity of the NICAM-TM CO_2 simulations. As Figure 6 is based on one-by-one coincident GOSAT−CME_AK CO_2 comparisons over airports selected by applying the thresholds of a 300-km distance and a 72-h time difference, we think that it is inappropriate to plot comparisons between 2.5°-gridded NICAM-TM and CME CO_2 data on the same figure. Alternatively, we have described the specific comparison in CO_2 growth rates between NICAM-TM simulation and surface observation data as follows:

"Furthermore, the CO_2 forward simulation of NICAM-TM for 2010−2012 showed a good agreement with in-situ CO_2 observations not only in seasonal cycles but also in trends in spite of using the fluxes optimized for 2006−2008; the simulated growth rate at the Minamitorishima station (e.g., Wada et al., 2011), which is one of the global stations of the Global Atmospheric Watch (GAW), was 2.4 ppm/yr for 2010−2012, while the growth rate based on in-situ observations was 2.2 ppm/yr."

"In addition, negative biases of TIR CO_2 data against NICAM-TM CO_2 data in all seasons slightly increased over time, judging from the mode values presented in the top left boxes of Table 3, although the increase in negative biases was not much evident as in the comparisons over airports shown in Figure 6; this may be partly because of slightly high growth rate of NICAM-TM simulations (2.4 ppm/yr) compared to in-situ observations (2.2 ppm/yr)."

We greatly appreciate your comment.



Reference figure. Time-series of observed (black) and simulated (red) CO_2 concentrations at the surface station at Minamitorishima. The observation data presented here were taken from the World Data Center for Greenhouse Gases (WDCGG). The observations have been conducted by JMA under the program of WMO/GAW. We would like to acknowledge the staff that supports the observations.

Page 9, line 5, other sources of negative biases: I'm not familiar with retrieval algorithms, but would any errors in cloud detection process cause retrieval errors in the low latitudes with enhanced convective activity? And H_2O or O_3 do not affect the CO_2 retrieval results?

Reply:

We appreciate your comment. As you pointed out, uncertainties in H_2O and O_3 data could also affect CO_2 retrievals, as shown in Figure 7(b) and (c) of Saitoh et al. (2009). The TIR V1 CO_2 retrieval algorithm (Saitoh et al., 2016) simultaneously retrieves H_2O and O_3 with CO_2, which could decrease the effect of their uncertainties on CO_2 retrieval results. However, water vapor is abundant in the tropics, so that we cannot completely deny the possibility of the effect of H_2O uncertainty on CO_2 retrieval results. Similarly, error in the judgement of cloud contamination may affect CO_2 retrieval results. We have added this point to the discussion part of the revised manuscript as follows:

"Although the effect of uncertainty in H_2O data on CO_2 retrieval results could be also decreased by simultaneous retrieval of H_2O with CO_2 in the TIR V1 algorithm, water vapor is abundant in the tropics, so that we cannot deny the possibility of its effect on CO_2 retrieval results. Similarly, error in the judgement of cloud contamination in low latitudes with high cloud occurrence frequency may affect CO_2 retrieval results."

Page 10, lines 29-30, "The CME data that determined the bias-correction values of the 20°S−20°N latitude band were concentrated in East Asia": I was confused with this sentence. Please see my general comment #2.

Reply:

As described above, we have replaced "East Asia" with "Southeast Asia" throughout the text. In the revised manuscript, we have listed specific airports (BKK, SIN, and CGK) where most CME data were obtained in the latitude band of 20°S−20°N as follows:

"The CME data that determined the bias-correction values of the 20°S−20°N latitude band were concentrated in Southeast Asia, as illustrated in Figure 1: BKK (Bangkok), SIN (Singapore), and CGK (Jakarta)."

We appreciate your comment.

Page 10, line 34 – page 11, line 1, "in most areas at 0°−20°N, and the negative biases were largest near airport locations in East Asia.": Same as above. Please see my general comment #2.

Reply:

As described above, we have replaced "East Asia" with "Southeast Asia" throughout the text. We appreciate your comment.

Page 11, lines 12-13, "More in-situ CO_2 data in the upper atmosphere in low latitudes": Hiaper Pole-to-Pole Observations (HIPPO) project observed latitudinal distributions of CO_2 concentrations in the free troposphere over the Pacific Ocean where mostly clean during 2009 to 2011 (e.g. Wofsy et al., 2011). The dataset has been used for transport model or satellite data validation (e.g. Wecht et al., 2012; Kulawik et al., 2013). The comparison with HIPPO data is out of the scope of this paper, but if the authors found some problems in using HIPPO data for validation, please write it in the discussion section or the introduction section.

Wofsy, S. C. et al.: HIAPER Pole-to-Pole Observations (HIPPO): fine-grained, global-scale measurements of climatically important atmospheric gases and aerosols, Phil. Trans. Roy. Soc. A: Math. Phys. Eng. Sci., 369, 2073–2086, doi:10.1098/rsta.2010.0313, 2011.

Reply:

We agree with you. The reason why we did not use HIPPO data in this study is that HIPPO campaign observations were conducted for limited periods (October−November in 2009, March−April in 2010, June−July in 2011, and August−September in 2011, after starting the regular operation of GOSAT) in limited areas (mainly over the Pacific Ocean), so that they are not suitable for evaluating season- and latitude-dependent biases in GOSAT/TANSO-FTS TIR CO_2 data. As you pointed out, however, HIPPO data themselves are useful to validate CO_2 vertical profiles observed by satellite-borne sensors and simulated in models. Following your advice, we have touched on HIPPO data in the discussion part of the revised manuscript as follows:

"Although HIAPER Pole-to-Pole Observations (HIPPO) data (Wofsy et al., 2011) are not suitable for a comprehensive validation study as in this study due to their limited observation periods, HIPPO CO_2 data are useful to validate CO_2 vertical profiles observed by satellite-borne sensors and simulated in models (Kulawik et al., 2013)."

We appreciate your comment.

Page 11, line 17, "Reconsideration of the setting of retrieval grid layers . . .": Why do the authors think the current setting of retrieval grid layers might not be suitable for retrievals and reconsideration might solve it?

Reply:

Total degree of freedom (defined as the trace of averaging kernel matrix) does not depend on the setting of retrieval grid layers theoretically. In this situation, partial degree of freedom for each retrieval grid layer (defined here as the diagonal element of averaging kernel matrix corresponding to each retrieval grid layer, see Saitoh et al. (2016)) should decrease as the number of retrieval grid layers increases. As illustrated in reference figure attached in Authors' reply to Referee #2, the total degrees of freedom of GOSAT/TANSO-FTS TIR V1 CO_2 data are on average 1.1−2.2 (depending on latitude and season), which means that we can derive information on CO_2 concentrations in more than 1−2 vertical layers independently from observations by the TIR band. In the TIR V1 Level 2 CO_2 retrieval algorithm, we have set 28 vertical grid layers. Judging from the total degree of freedom of the TIR CO_2 data and the relatively small partial degree of freedom for each vertical grid layer, we think we should reconsider the setting of retrieval grid layers.

Page 11, line 20, "during the JJA seasons of 2011 and 2011": Does this mean "2011 and 2012"?

Reply:

We have modified the sentence. We appreciate you pointing out our mistake.

Figs.3: The Y axis is described in altitude, not in pressure as seen in the following plots. For easy reference, I would suggest adding a 2nd Y axis in pressure or adding a column in Table 1 to show altitude [km] for each pressure levels. (Rough altitudes from International Standard Atmosphere or the same kind might be enough for this purpose.

Reply:

Following your suggestion, we have added a second vertical axis (y-axis) in pressure in Figure 3 of the revised manuscript. Here, we have taken pressure levels corresponding to the measurement location of GOSAT/TANSO-FTS TIR data shown in the figure.

Fig.4: Please replace “Altitude [km] in Y axis label with “Pressure [hPa]”.

Reply:

We have corrected the label of the vertical axis (y-axis) of Figure 4 of the revised manuscript. We appreciate you pointing out our mistake.

Fig.7: I think drawing zero lines (i.e. no bias) in each panel makes the bias correction validity more visible.

Reply:

Following your advice, we have drawn zero lines in each of the four panels of Figure 7 of the revised manuscript. We have also drawn zero lines in Figure 8 and 9 to show differences between each histogram clearly. We appreciate your suggestion.

Fig.7 caption “Thick and dashed lines indicate the biases of the original TIR CO_2 data (no bias correction) and bias-corrected TIR CO_2 data, respectively.“:

1. On my screen, all lines in each panel seem to have same line thickness. Do the authors mean “solid and dashed lines”?

2. This sentence does not match the main text which says that thick lines are bias-corrected values.

Reply:

We appreciate you pointing out our mistake.

1. We have replaced “thick lines” with “solid lines” and exchanged “solid” for “dashed” in the caption for Figure 7 of the revised manuscript as follows:

“Dashed and solid lines indicate the biases of the original TIR CO_2 data (no bias correction) and bias-corrected TIR CO_2 data, respectively.”

2. We have replaced “thick lines” with “solid lines” in the sentences related to Figure 7 in the revised manuscript.

Fig.11, gray shade: Could the authors explain what gray zones in the figure are? (No data or out of color scale?)

Reply:

Gray color in Figure 11 means no GOSAT/TANSO-FTS TIR CO_2 data in a 2.5° grid area. Following your advice, we have explained the meaning of gray color in the caption for Figure 11 of the revised manuscript as follows:

“There are no GOSAT/TANSO-FTS TIR CO_2 data in gray-shaded areas.”

Reply to Referee #2,

Overall, this is a good paper dealing with difficult but necessary bias corrections to TANSO-FTS observations of mid-troposphere CO_2. It's a tricky subject, but the methodology is generally sound. However, the paper is difficult to follow in some sections, and in many cases, the figures need some improvement and clarification. I would recommend publication after some revisions in the text, and if the authors could better address the issue of the number of layers in the forward model (see comment for page 10, line 32 below.)

General comment: Throughout the paper, the authors refer to the retrieval layers by number (layer 3, layer 4, etc.), rather than, say, its log mean pressure. These layer numbers are specific to their algorithm, and referencing the layers by number is a little burdensome to the reader, even where the pressures are provided. For example, Page 6, line 23 reads "Saitoh et al. (2016) showed that TIR V1 CO_2 data agreed well with CME level flight CO_2 data in the UT region corresponding to retrieval layers 9 and 10." This would read better if the pressures were given instead of the layer numbers. I suggest they prepare a table listing the retrieval layer numbers, layer boundary pressures, and the log-mean pressures of the layers (similar to Table 1 of Saitoh et al., 2016), and then just refer to a layer by its mean pressure rather than its number.

Reply:

We greatly appreciate your comments. As described above, we have added Table 1 to show representative pressure levels of each of the retrieval grid layers used in the GOSAT/TANSO-FTS TIR V1 L2 CO_2 retrieval processing and referred to the retrieval grid layers by the representative pressure levels instead of retrieval grid numbers. In Table 1, we have kept the retrieval grid numbers for the convenience of TIR CO_2 data users. In the TIR V1 L2 CO_2 retrieval algorithm, we have calculated representative pressure level P_{rlay}, which is thermodynamically mean pressure level, by the following expression [Gallery et al., 1983]:

$$P_{rlay} = \left\{ \frac{H_P H_\rho}{H_P + H_\rho} \left(P_{rlev\_j}\,\rho_{rlev\_j} - P_{rlev\_j+1}\,\rho_{rlev\_j+1} \right) \right\} / \left\{ H_\rho \left(\rho_{rlev\_j} - \rho_{rlev\_j+1} \right) \right\}$$

$$H_P = \frac{-\Delta z}{\log_e \left(P_{rlev\_j+1} / P_{rlev\_j} \right)}$$

$$H_\rho = \frac{-\Delta z}{\log_e \left(\rho_{rlev\_j+1} / \rho_{rlev\_j} \right)} ,$$

$$\Delta z = \log_e \frac{P_{rlev\_j+1}}{P_{rlev\_j}} \times -\frac{Rd}{g} \times \frac{\left| T_{rlev\_j+1} - T_{rlev\_j} \right|}{2}$$

where P_{rlev_j} and P_{rlev_j+1} are lower and upper pressure levels of each retrieval grid layer, respectively, T_{rlev_j} and T_{rlev_j+1} are temperatures at the two pressure levels, ρ_{rlev_j} and ρ_{rlev_j+1} are air densities at the two pressure levels, Rd is the gas constant, and g is the acceleration of gravity. Representative pressure levels change depending on temperature, which are stored in each of the

TIR V1 L2 CO_2 data files, but their variabilities are quite small. In Table 1, we have presented the averages of representative pressure levels of each retrieval grid layer calculated by using all GOSAT/TANSO-FTS measurements in 2010.

Page 1, line 14: "…good spatial representability." It's not obvious what 'representability' means here. Would "resolution and precision" be a better phrase to use?

Reply:

CO_2 concentrations in the free troposphere are well mixed compared to the concentrations near the surface and less affected by local point sources of CO_2; in that context, observations in the free troposphere can obtain CO_2 concentrations representative of regions, which can be dealt with in a global model estimating CO_2 surface fluxes. In the revised manuscript, we have modified the sentence to clarify this point as follows:

"CO_2 observations in the free troposphere can be useful for constraining CO_2 source and sink estimates at the surface due to their representativeness being away from local point sources of CO_2."

Page 1, line 24: "(retrieval layers 5−6), …" It's not necessary to get into the details of their retrieval method in the abstract.

Reply:

We have deleted the phrase in the abstract of the revised manuscript following your advice.

Page 2, line 3: Suggest changing "(e.g., Gurney et al., 2002 Gurney et al., 2004)" to "(e.g., Gurney et al., 2002; 2004)".

Reply:

Following your suggestion, we have modified the text in how to cite the references.

Page 2, line 24: "spatial representability." Again, not obvious what it means here.

Reply:

XCO_2 data obtained by measurements utilizing short-wave infrared (SWIR) band contained information on CO_2 concentrations near the surface compared to free tropospheric CO_2 measurements utilizing TIR band. However, satellite-borne sensors have relatively large field-of-views, and therefore their XCO_2 data are averaged concentrations in their field of views of several kilometers that are not too much affected by strong local point sources of CO_2. In the revised manuscript, we have modified the sentence as follows:

"Global XCO_2 data based on satellite observations are averaged concentrations in their field of views of several kilometers that are not too much affected by strong local point sources of CO_2, and have therefore been used to estimate surface CO_2 fluxes (Maksyutov et al., 2013; Saeki et al., 2013a; Chevallier et al., 2014; Basu et al., 2013, 2014; Takagi et al., 2014)."

Page 3, line 16: Suggest changing "…and has continued CO_2 and CH_4 operational measurements for approximately eight years." to "and has continued operational measurements of CO_2 and CH_4 for approximately eight years.

Reply:

Following your suggestion, we have modified the sentence.

Page 3, line 23: Suggest shortening "These studies showed the following: 1) TIR UT CO_2 data agreed…" to "These studies showed: 1) TIR UT CO_2 data agreed…"

Reply:

Following your suggestion, we have modified the sentence.

Page 5, line 14: Suggest more explanation of why the averaging kernels are applied to the CME data and then comparison made. This would be useful to the reader not well versed in averaging kernels etc.

Reply:

Following your advice, we have added more explanation of why we should apply TIR CO_2 averaging kernel functions to CME aircraft profiles as follows:

"Observations by satellite-borne nadir-viewing sensors like TANSO-FTS have much lower vertical resolution than aircraft observations. Therefore, we smoothed the CME_obs. profile to fit its vertical resolution to the vertical resolution of corresponding TIR CO_2 profile by applying TIR CO_2 averaging kernel functions (AK) to the CME_obs. profile, as follows (Rodgers and Connor, 2003):"

Page 6, Section 4.2: It's not obvious why an "average" averaging kernel can be applied and not sometimes be misleading. In addition to the effect of instrument parameters (SNR, spectral resolution, view angle etc.) and assuming clear scenes only, the averaging kernel could vary by temperature gradient and thermal contrast with the surface. How much does an averaging kernel vary within a grid box? It would help if the authors briefly explain why they're using an averaged AK here and discuss the limitations of doing so.

Reply:

We agree with you. TIR CO_2 averaging kernel functions depend on TIR measurement spectral noise, a priori CO_2 profile variability, and CO_2 Jacobians. In the TIR V1 L2 CO_2 retrieval algorithm, we set covariance matrices of the TIR measurement noise and a priori CO_2 profile in the same manner for all TIR CO_2 measurements, as described in Saitoh et al. (2016). The CO_2 Jacobians depend on temperature and CO_2 profiles, and therefore change with location and time. For a validation purpose based on one-by-one comparisons like TIR versus CME CO_2 profiles, we should apply corresponding TIR CO_2 averaging kernel functions, not averaged one. On the other hand, the purpose of comparisons between TIR and NICAM-TM CO_2 data is to evaluate the bias-correction values determined for each vertical layer, latitude band, and season. In addition, TIR CO_2 averaging kernel functions showed nearly identical structures with each other when collected for each 2.5° grid in one month, which means that applying the monthly averaged TIR CO_2 averaging kernel functions did not affect the conclusions of this study. From this standpoint, using monthly averaged TIR CO_2 averaging kernel functions instead of individual one is enough for our purpose. In the revised manuscript, we have added one paragraph in Section 4.2 and discussed the effect of using monthly averaged TIR CO_2 averaging kernel functions on our analysis. We appreciate your comments.

Page 7, line 14 "In addition, negative biases of TIR CO_2 data against NICAM-TM CO_2 data increased by 1 ppm or less per year in all seasons, judging from the mode values, although the increase in negative biases was not evident in the comparisons over airports shown in Figure 6." I did not quite understand what is meant by this. Do they mean the bias varied by 1ppm or less?

Reply:

We intended to say the following: negative biases of TIR CO_2 data against NICAM-TM CO_2 data seemed to increase over time, judging from each of the mode values for the three years and the rate of the increase was around and less than 1 ppm; however, the increase in the negative biases against NICAM-TM CO_2 data was not evident as was the case with the negative biases against CME CO_2 data discussed in Section 5.1. In the revised manuscript, we have modified the sentence as follows:

"In addition, negative biases of TIR CO_2 data against NICAM-TM CO_2 data in all seasons slightly increased over time, judging from the mode values, although the increase in negative biases was not much evident as in the comparisons over airports shown in Figure 6."

Page 8, line 27: Typo: "… in the LT and ML regions." Did they mean "MT" regions?

Reply:

We have modified the sentence. We appreciate you pointing out our mistake.

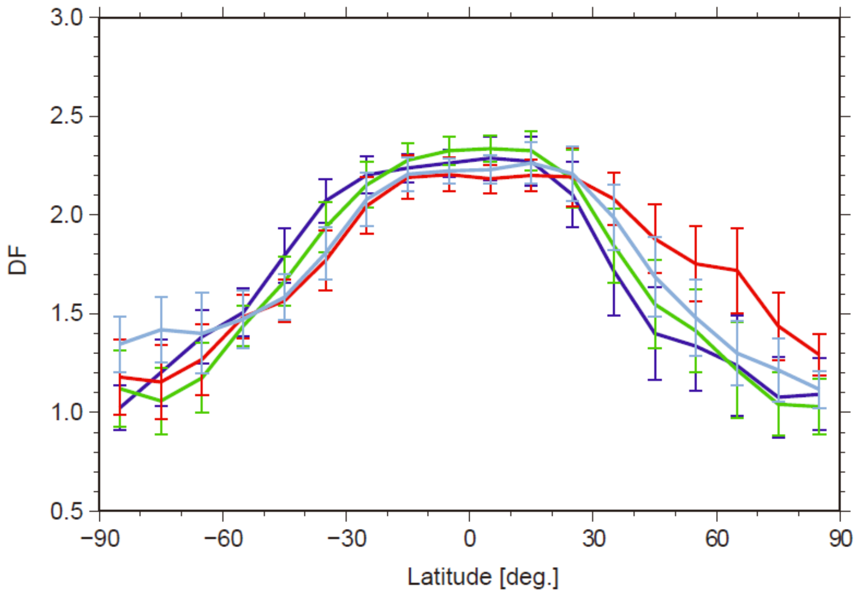
Page 9, line 13: "As shown in Figure 6, the largest negative biases in TIR V1 CO_2 data existed in the MT *region in middle and low latitudes during spring and summer, where TANSO-FTS TIR measurements have relatively large sensitivity to CO_2 concentrations and thus the retrievals are less constrained to a priori concentrations." Some kind of comparison is in order to quantify the difference in CO_2 sensitivity here – say average row-sum of averaging kernels, or total DOFS as a function of latitude.*

Reply:

We totally agree with you. We have modified the related sentences for consistency with the sentences in the second paragraph of Section 5.1, and then provided information on degrees of freedom of TIR V1 CO_2 data in low latitudes where the largest negative biases existed:

"As shown in Figure 6, the largest negative biases in TIR V1 CO_2 data existed in the MT region in low latitudes (20°S−20°N) during the JJA season. Degrees of freedom (DF) of TIR V1 CO_2 data were highest in low latitudes, exceeding 2.2 in all seasons, which means retrieved CO_2 concentrations there contained more information coming from TANSO-FTS TIR L1B spectra and thus were relatively less constrained to a priori concentrations."

The DF values have been referred from the below figure that shows monthly averaged DF values for each 10° latitude in January (blue), April (green), July (red), and October (light blue) in 2010.



Reference figure. Monthly averaged DF values of TIR V1 CO_2 data for each 10° latitude in January, April, July, and October 2010, shown by blue, green, red, and light blue lines, respectively. Here, GOSAT/TANSO-FTS observations with high elevated areas (surface pressure less than 736 hPa) were excluded.

Page 9, line 15: "This implies that biases in L1B spectra are a major cause of the negative biases in retrieved CO_2 concentrations, as Saitoh et al. (2016) noted in the UT region." The wording is confusing. Does this mean there are biases in the L1b radiances related to latitude and season, or are there fitting biases from the retrieval algorithm? Judging from the rest of the paragraph where the authors write about *retrieval of surface parameters, I think they're referring to fitting bias, but whatever the bias is, it should be explicitly described.*

Reply:

According to comparisons between TANSO-FTS TIR and S-HIS radiance spectra (Kataoka et al., 2014) and theoretical radiance error estimations (Kuze et al., 2016), TANSO-FTS TIR L1B radiance spectra had considerable biases. In low latitudes, retrieved CO_2 data contained more information coming from TANSO-FTS TIR L1B spectra judging from their highest DF values. This means that the effect of the L1B radiance biases should be also largest in TIR CO_2 data in low latitudes. The magnitude of the TIR L1B radiance biases may change by scene, but we have not yet drawn any conclusion on the dependence of the radiance biases on time, location, viewing angle, thermal condition of TANSO-FTS instrument, and so on. As the related three paragraphs in Discussion were less organized, we have reorganized the discussion on the relation between L1B radiance biases and L2 CO_2 negative biases against CME CO_2 data in the revised manuscript.

Page 10, line 4: "From these results, we conclude that using the 10-μm band in conjunction with the 15-μm and 9-μm bands in the V1 retrieval algorithm is a probable cause of the negative biases in retrieved CO_2 concentrations in the LT and MT regions." While I don't disagree with this, this would be more convincing if the authors compared their results using the different mixes of CO_2 bands directly against the aircraft measurements.

Reply:

We totally agree with you. We have also showed nearby CME CO_2 profiles by gray lines in Figure 10 of the revised manuscript other than TIR CO_2 retrieval results. We appreciate your suggestion.

Page 10, Line 13: "According to Figure 13 in Kuze et al. (2016), there was no distinct uncertainty in the 10-μm band in the latest version of the TANSO-FTS TIR spectra." The wording of this leaves me uncertain of what they're claiming. Uncertainty of linestrengths or low fitting residual? Are they saying that using the 10 micron band of CO_2 does not add significant bias? This should be clarified.

Reply:

Kuze et al. (2016) performed theoretical estimation of radiance biases of TANSO-FTS TIR L1B V161 and newer version V201 spectra. The radiance biases inherent in the TANSO-FTS TIR L1B spectra were attributable to several calibration issues, mainly due to polarization correction. According to theoretical calculations shown in Figure 13 in Kuze et al. (2016), there were no distinct radiance biases in the 10-μm band (930−990 cm^{-1}) in the latest version of the

TANSO-FTS TIR spectra. If it is true for observed TIR radiances, our test retrievals imply that simultaneous retrieval of surface parameters for TIR spectra at the 10-μm band with less radiance bias worsened CO_2 retrieval results. We have clearly stated this in the revised manuscript.

Page 10, paragraph beginning line 17: As noted earlier, it would really help the reader if the authors referred to the retrieval layers by pressure and not layer number.

Reply:

Following your advice, we have referred to the lower and upper pressure levels of the two retrieval grid layers that we focused on.

Page 10, line 32: "In retrieval from TIR spectra, the more atmospheric layers in which we retrieve CO_2 concentrations, the lower the information content of the retrieval result in each layer becomes; as a result, the retrieved concentrations are constrained by a priori model data. Thus, there is a high possibility of large biases in retrieved TIR CO_2 concentrations in low latitudes." This assertion needs to be tested. It is true that with more layers, the information is spread out more, but the overall information content, as measured by the degrees-of-freedom-of-signal (trace of the averaging kernel) can be the same or very similar, as can the retrieved profiles (depending on what the off-diagonals are for the a priori background covariance.) It's quite possible that if the background a priori is biased, then a TIR retrieval can also be biased not because of the number of retrieval layers, but, particularly at low latitudes, because of water vapor interference, undetected boundary- layer clouds changing the thermal contrast with the surface, or biases in the temperature. Again, this needs to be tested, or the statement removed or at least reworded as a hypothesizing.

Reply:

We totally agree with you. Our wording in the original manuscript leads to misunderstanding. We here intended to say that TIR CO_2 retrieval were somewhat constrained by a priori concentrations. In the MT region in low latitudes, a priori CO_2 concentrations taken from the NIES-TM05 model probably have larger uncertainties due to the parameterization of vertical transport. Therefore, there is a possibility of more biases attributed to the a priori uncertainties in retrieved TIR CO_2 data there. Following your suggestion, we have removed the related statement and modified the sentences in the revised manuscript as follows:

"In low latitudes, there are relatively strong updrafts, and thus there are larger uncertainties among models than in other areas due to differences in the parameterization of vertical transport. Therefore, a priori CO_2 concentrations taken from the NIES-TM05 model (Saeki et al., 2013b) probably have larger uncertainties in the MT region in low latitudes. As retrieved TIR CO_2 concentrations were to some extent constrained by a priori concentrations, they possibly had more biases attributed to the a priori uncertainties in the MT region in low latitudes."

We greatly appreciate your comment.

Figure 5: It would be much clearer to the reader if they provided guidance to the different panels and lines in a legend box on the figure, rather than only in the caption. It would also help, for a reader skimming the paper, to describe what "CME_AK CO_2" means in the caption as well as the text of the paper.

Reply:

Following your advice, we have provided information on seasons in each panel and described each line in both left and right sides of the panel (a). In the caption of the revised manuscript, we have described what CME_AK CO_2 means as follows:

"The CME_AK CO_2 data are CME CO_2 data to which TIR CO_2 averaging kernel functions are applied."

Figure 6: Use pressures and not layer numbers on vertical axis. It would also be better if latitude information and season (line color) were provided as a legend on the figure. It would help if the lines in the top panels had slight vertical offsets to clarify how different the error bars are from each other.

Reply:

Following your advice, we have presented the representative pressure levels of the six retrieval grid layers shown in Table 1 instead of their layer numbers. We have provided information on latitude bands and colors for seasons as a legend and slightly shifted horizontal bars for 1-σ standard deviations in Figure 6 of the revised manuscript. We appreciate your comments.

Figure 7: It's not clear here (or in the text) at what pressures they are comparing avg CO_2 with NICAM. The contrast between the mid-gray and light-gray lines is not enough to easily distinguish between them.

Reply:

Figure 7 includes all comparison results between TIR and NICAM-TM CO_2 data in the six retrieval grid layers from 736 to 287 hPa (retrieval layers 3−8). In the revised manuscript, we have stated this clearly in the revised manuscript as follows:

"Figure 7 shows the frequency distributions of differences in monthly averaged CO_2 concentrations between TIR and NICAM-TM CO_2 data in all retrieval layers from 736 to 287 hPa in all 2.5° grids over the latitude range of 40°S to 60°N.".

Following your advice, we have presented the lower and upper pressure levels of the six retrieval layers that we focused on and used red and blue colors instead of light-gray and mid-gray colors in Figure 7 of the revised manuscript. We appreciate your comments.

Figure 8: Please use pressures instead of layer numbers. Again, the contrast between the mid-gray and

light-gray lines is not enough to easily distinguish between them.

Reply:
Following your advice, we have presented the lower and upper pressure levels of each set of the six retrieval grid layers that we focused on and used red and blue colors instead of light-gray and mid-gray colors in Figure 8 of the revised manuscript.

Figure 9: Again, please state the pressures instead of "layer 7-8."

Reply:
Following your advice, we have modified Figure 9 to present the lower and upper pressure levels of the two retrieval grid layers that we focused on.

Figure 10: Please also describe the lines and the location/times the different panels represent as a legend rather than just in the caption.

Reply:
Following your advice, we have modified Figure 10: we have separated the two results of Figure 10(b) and discarded the result of Figure 10(a) of the original manuscript to simplify the figure, provided information on the locations (both over Narita airport) and dates ((a) April 1, 2010 and (b) April 30, 2010) of the two results in the caption and each of the panels, and described each of the five lines in the panel (b).

In the revised manuscript showing the changes made that is attached below, we have showed the changes that we made to address the comments by Referee #1 by blue color, and the changes that we had made to address the comments by Referee #2 and have been already reflected in AMTD by red color.

Bias assessment of lower and middle tropospheric CO_2 concentrations of GOSAT/TANSO-FTS TIR Version 1 product

Naoko Saitoh[1], Shuhei Kimoto[1*], Ryo Sugimura[1**], Ryoichi Imasu[2], Kei Shiomi[3], Akihiko Kuze[3], Yo~~u~~suke Niwa[4], Toshinobu Machida[5], Yousuke Sawa[4], and Hidekazu Matsueda[4]

[1]Center for Environmental Remote Sensing, Chiba University, Chiba, 263-8522, Japan
[2]Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, 277-8564, Japan
[3]Japan Aerospace Exploration Agency, Tsukuba, 305-8505, Japan
[4]Meteologotical Research Institute, Tsukuba, 305-0052, Japan
[5]National Institute for Environmental Studies, Tsukuba, 305-8506, Japan
[*]Now at the Japan Research Institute, Tokyo, 141-0022, Japan
[**]Now at Fujitsu FIP Corporation, Tokyo, 105-8668, Japan

Correspondence to: Naoko Saitoh (nsaitoh@faculty.chiba-u.jp)

Abstract. CO_2 observations in the free troposphere can be useful for constraining CO_2 source and sink estimates at the surface due to their ~~good spatial~~ representativeness being away from local point sources of CO_2~~bility~~. The thermal infrared (TIR) band of the Thermal and Near Infrared Sensor for Carbon Observation (TANSO)−Fourier Transform Spectrometer (FTS) on board the Greenhouse Gases Observing Satellite (GOSAT) has been observing global CO_2 concentrations in the free troposphere for about 8 years, and thus could provide a dataset with which to evaluate the vertical transport of CO_2 from the surface to the upper atmosphere. This study evaluated biases in the TIR version 1 (V1) CO_2 product in the lower troposphere (LT) and the middle troposphere (MT) (736−287 hPa), on the basis of comparisons with CO_2 profiles obtained over airports using Continuous CO_2 Measuring Equipment (CME) in the Comprehensive Observation Network for Trace gases by AIrLiner (CONTRAIL) project. Bias-correction values are presented for TIR CO_2 data for each pressure layer in the LT and MT regions during each season and in each latitude band: 40°S–20°S, 20°S–20°N, 20°N–40°N, and 40°N–60°N. TIR V1 CO_2 data had consistent negative biases of 1−1.5% compared with CME CO_2 data in the LT and MT regions, with the largest negative biases at 541−398 hPa ~~(retrieval layers 5−6)~~, ~~especially in low latitudes during northern summer (up to 7.3 ppm),~~ partly~~likely~~ due to the use of ~~spectra at a~~ 10-µm CO_2 absorption band in conjunction with 15-µm and 9-µm absorption bands in the V1 retrieval algorithm. Global comparisons between TIR CO_2 data to which the bias-correction values were~~had been~~ applied and CO_2 data simulated by Nonhydrostatic ICosahedral Atmospheric Model (NICAM)-based transport model (TM) confirmed the validity of the bias-correction values evaluated over airports in limited areas. In low latitudes in the upper MT region (398−287 hPa), however, TIR CO_2 data in northern summer were overcorrected by these bias-correction values; this is because the bias-correction values were determined using comparisons mainly over airports in Southe~~E~~ast Asia where CO_2 concentrations in the upper atmosphere display relatively large variations due to strong updrafts.

1. Introduction

CO_2 in the atmosphere is the most influential greenhouse gas (IPCC, 2013 and references therein). Many studies have been conducted to estimate the sources and sinks of atmospheric CO_2 using both observational data and transport models (e.g., Gurney et al., 2002; ~~Gurney et al.,~~ 2004). In CO_2 inversion studies, accurate atmospheric CO_2 observations with ~~good~~ spatial representativeness~~bility~~ are desirable, which can be obtained from elevated sites such as tall towers and mountains or over the ocean. Patra et al. (2006) demonstrated the robustness of CO_2 surface flux estimation using CO_2 data obtained solely from ocean sites compared to data obtained from both ocean and land sites; this was because the models discussed therein were unable to successfully simulate CO_2 data over land, as these sites were more affected by local point sources of CO_2. Uncertainties in atmospheric transport processes also result in differences in CO_2 surface fluxes estimated by inverse models. CO_2 is chemically inactive, and thus long-range transport processes as well as surface fluxes determine its horizontal distribution and seasonal cycle in the atmosphere (Miyazaki et al., 2008; Barnes et al., 2016). The treatment of vertical transport of CO_2 also produces differences in simulated CO_2 concentrations in the free troposphere among transport models unrelated to surface fluxes (Niwa et al., 2011a). Therefore, it is needed to observe CO_2 concentrations over land that are not strongly affected by local point sources of CO_2 emissions, as well as CO_2 concentrations in the free troposphere that can evaluate vertical CO_2 transport from the surface in transport models.

Satellite-borne nadir-viewing sensors can observe averaged CO_2 concentrations, with horizontal resolution ranging from several kilometers to tens of kilometers. Column-averaged dry-air mole fractions of CO_2 (XCO_2) have been observed utilizing CO_2 absorption bands in the shortwave infrared (SWIR) regions at around 1.6 and/or 2.0 μm by satellite-borne sensors such as the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) on the Environmental Satellite (ENVISAT) (Buchwitz et al., 2005; Barkley et al., 2006), the Thermal and Near Infrared Sensor for Carbon Observation (TANSO)–Fourier Transform Spectrometer (FTS) on the Greenhouse Gases Observing Satellite (GOSAT) (Yoshida et al., 2011, 2013; O'Dell et al., 2012; Butz et al., 2011; Cogan et al., 2012), and the Orbiting Carbon Observatory 2 (OCO-2) (Crisp et al., 2017; Connor et al., 2016). Global XCO_2 data based on satellite observations are averaged concentrations in their field of views of several kilometers that are not too much affected by strong local point sources of CO_2~~have relatively good spatial representability~~, and have therefore been used to estimate surface CO_2 fluxes (Maksyutov et al., 2013; Saeki et al., 2013a; Chevallier et al., 2014; Basu et al., 2013, 2014; Takagi et al., 2014). CO_2 concentrations in the free troposphere can be obtained by satellite-borne sensors with thermal infrared (TIR) bands at around 4.6, 10, and/or 15 μm, provided by the following sensors: the High-Resolution Infrared Sounder (HIRS) (Chédin et al., 2002, 2003, 2005), the Interferometric Monitor for Greenhouse Gases (IMG) (Ota and Imasu, 2016), the Atmospheric Infrared Sounder (AIRS) (Crevoisier et al., 2004; Chahine et al., 2005; Maddy et al., 2008; Strow and Hannon, 2008), the Tropospheric Emission Spectrometer (TES) (Kulawik et al., 2010, 2013), the Infrared Atmospheric Sounding Interferometer (IASI) (Crevoisier et al., 2009), and the TANSO-FTS (Saitoh et al., 2009, 2016). Furthermore, CO_2 concentrations in several atmospheric layers within the free troposphere can be retrieved separately from high-resolution TIR spectra (Saitoh et al., 2009; Kulawik et al., 2013). Such vertical CO_2 data offer a good constraint for CO_2 surface flux estimates (Kulawik et al., 2010), and have the potential to evaluate the vertical transport of CO_2 from the surface to the upper atmosphere, if they have sufficient accuracy.

Previously, the data quality of CO_2 product from the GOSAT/TASNO-FTS TIR band has been examined in the upper troposphere and the lower stratosphere (UTLS) region, where TIR observations have the most sensitivity to CO_2 concentrations. Saitoh et al. (2016) evaluated biases in UTLS (287−162 hPa) CO_2 data of TIR version 1 (V1) Level 2 (L2) product for the year 2010 through comparisons with UTLS CO_2 data collected with broad spatial coverage by Continuous CO_2 Measuring Equipment (CME) in the Comprehensive Observation Network for Trace gases by AIrLiner (CONTRAIL) project. We evaluated the biases, growth rates, and seasonal variations in the TIR V1 UT CO_2 data for three years, from 2010 to 2012 (Saitoh et al., 2017). In this study, we validated the TIR V1 CO_2 product in the lower troposphere (LT) and the middle troposphere (MT) (736−287 hPa) by comparing them with CONTRAIL CME CO_2 profiles over airports, and calculated bias-correction values for the TIR CO_2 data, based on comparisons by latitude, pressure layer, and season from 2010 to 2012. We then examined the validity of the bias-correction values evaluated in limited areas over airports by comparing TIR CO_2 data before and after applying the bias-correction values to CO_2 data simulated using Nonhydrostatic ICosahedral Atmospheric Model (NICAM)-based transport model (TM) (Niwa et al., 2011b).

2. GOSAT/TANSO-FTS and CONTRAIL CME observations

GOSAT, launched on 23 January 2009, and has continued operational measurements of CO_2 and CH_4 operational measurements for approximately eight years. TANSO-FTS on board GOSAT consists of three bands in the SWIR region and one in the TIR region (Kuze et al., 2009). The TIR band of TANSO-FTS makes observations both in daytime and nighttime, unlike the SWIR band. We analyzed the latest CO_2 product from the TIR band of TANSO-FTS, the TIR V1 L2 CO_2 product. The TIR V1 L2 CO_2 product was generated from TANSO-FTS version 161.160 (V161) Level 1B (L1B) radiance spectra. Saitoh et al. (2016) described the retrieval algorithm for the TIR V1 L2 CO_2 product in detail. In the TIR V1 L2 algorithm, CO_2 concentrations are retrieved in 28 vertical grid layers from the surface to 0.1 hPa. Saitoh et al. (2016) and Saitoh et al. (2017) evaluated biases in TIR V1 CO_2 data in the UTLS region corresponding to retrieval layers 9−11 (287−162 hPa) and calculated growth rates and amplitudes of seasonal variations in TIR V1 UT CO_2 data. These studies showed the following: 1) TIR UT CO_2 data agreed with CME CO_2 data to within 0.1% and an average of 0.5% in the Southern and Northern Hemispheres, respectively; 2) these data exhibited negative biases larger than 2 ppm in spring and summer in northern low and middle latitudes; 3) their negative biases increased over time partly due to constraint by a priori data with low growth rates taken from National Institute for Environmental Studies (NIES) transport model, NIES-TM05 (Saeki et al., 2013b); and 4) they displayed more realistic seasonal variations in UT CO_2 concentrations than a priori data. In this study, we validated the quality of TIR V1 CO_2 data in the LT (736−541 hPa) and MT (541−287 hPa) regions, defined as retrieval layers 3−4

~~(736−541 hPa) and 5−8 (541−287 hPa), respectively~~, by comparing them to CONTRAIL CME CO_2 data. Table 1 shows pressure levels of retrieval grid layers of the TIR V1 CO_2 product that this study focused on.

CONTRAIL is a project to observe atmospheric trace gases, such as CO_2 and CH_4, using two types of instruments installed on commercial aircraft operated by Japan Airlines (JAL) starting in 2005. Of the two instruments, CME can observe CO_2 concentrations more frequently over a wide area (Machida et al., 2008). See Machida et al. (2008) and Machida et al. (2011) for details about CME CO_2 observations. This study used CO_2 data obtained with CME during the ascent and descent flights over several airports from 2010 to 2012. Figure 1 shows the locations of the airports used here, which fall in the latitude range of 40°S to 60°N.

3. NICAM-TM CO_2 data

We used atmospheric CO_2 data simulated by NICAM-TM (Niwa et al., 2011b) for global comparison with TANSO-FTS TIR CO_2 data. NICAM has quasi-homogeneous grids, with horizontal grids generated by recursively dividing an icosahedron. The NICAM simulations used in this study were performed with a horizontal resolution of around 240 km, which corresponds to the horizontal resolution when an icosahedron is divided five times (“glevel-5”). See Tomita and Satoh (2004) and Satoh et al. (2008, 2014) for details of NICAM. The transport model version of NICAM, NICAM-TM, has been developed and used for atmospheric transport and source/sink inversion studies of long lived species such as CO_2 (Niwa et al., 2011a,b, 2012, 2017).

In this study, simulation of NICAM-TM used inter-annually varying flux data of fossil fuel emissions (Andres et al., 2013) and biomass burnings (van der Werf et al., 2010), and the residual natural fluxes from the inversion of Niwa et al. (2012), which mostly represent fluxes from the terrestrial biosphere and oceans. The inversion analysis of Niwa et al. (2012) was performed for 2006−2008 and the three-year-mean fluxes were used in this study. In the inversion analysis, CONTRAIL CO_2 data obtained during ascending, descending, and cruise level flights were categorized into four vertical bins: 575–625, 475–525, 375–425, and 225–275 hPa, and the binned CONTRAIL CO_2 data were then~~The NICAM-TM CO_2 data used here~~ incorporated ~~CONTRAIL CO_2 data~~ into the inverse model, in addition to surface CO_2 data (Niwa et al., 2012). ~~CONTRAIL CO_2 data obtained during ascending, descending, and cruise level flights were categorized into four vertical bins: 575–625, 475–525, 375–425, and 225–275 hPa. The binned CONTRAIL CO_2 data were then incorporated into NICAM-TM inversion calculations to estimate surface CO_2 fluxes.~~ Niwa et al. (2012) showed that incorporating the CONTRAIL CO_2 data into the surface flux inversion model improved CO_2 concentration simulation compared with a simulation using surface CO_2 data only. They also demonstrated that the simulated CO_2 concentrations based on CONTRAIL CO_2 data showed better agreement with independent upper atmospheric CO_2 data obtained in the Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container (CARIBIC) project (Brenninkmeijer et al., 2007). Furthermore, the CO_2 forward simulation of NICAM-TM for 2010−2012 showed a good agreement with in-situ CO_2 observations not only in seasonal cycles but also in trends in spite of using the fluxes optimized for 2006−2008; the simulated growth rate at the

Minamitorishima station (e.g., Wada et al., 2011), which is one of the global stations of the Global Atmospheric Watch (GAW), was 2.4 ppm/yr for 2010−2012, while the growth rate based on in-situ observations was 2.2 ppm/yr.

4. Methods

4.1 Bias assessment of TIR CO_2 data using CME observations

Vertical distribution of CO_2 concentrations can be obtained by CME during the ascent flights from departure airports and the descent flights to destination airports. Figure 2 shows the flight tracks of CME ascending and descending observations over Narita airport, Japan (35.8°N, 140.4°E) in 2010. CME CO_2 data were regarded as part of ~~the~~ CO_2 vertical profiles, with maximum altitudes around 12 km, and were obtained within 3−4° of latitude and longitude of the airport. Therefore, we set the threshold for selecting coincident pairs of TANSO-FTS TIR and CME CO_2 profiles for comparison to be a 300-km distance from each of the airports shown in Figure 1.

For each of the coincident pairs, we calculated the weighted average of discrete CME CO_2 data in a vertical layer, "CME_raw", represented by black circles in Figure 3(a), with respect to the center pressure levels of each of the 28 vertical grid layers of TIR CO_2 data. When there were no corresponding CME CO_2 data in lower retrieval grid layers, CO_2 concentration at the lowest altitude observed by CME was assumed to be constant down to the lowest retrieval grid layer. Similarly, the uppermost CO_2 concentration observed was assumed to be constant up to the center pressure level of the retrieval grid layer including the tropopause, identified based on temperature lapse rates of Global Spectral Model Grid Point Values from the Japan Meteorological Agency (JMA-GPV) interpolated to the location of CME measurement. In retrieval grid layers above the tropopause, CO_2 concentrations were determined based on CO_2 concentration gradients calculated from NICAM-TM CO_2 data near a CME measurement location. We collected eight NICAM-TM CO_2 data points from four model grids adjacent to a CME measurement location at times before and after CME measurement, and linearly interpolated them to the CME measurement location and time. The red line in Figure 3(a) shows a CO_2 vertical profile determined in this manner. This CO_2 vertical profile was designated as "CME_obs." profile. Observations by satellite-borne nadir-viewing sensors like TANSO-FTS have much lower vertical resolution than aircraft observations. Therefore, we smoothed the CME_obs. profile to fit its vertical resolution to the vertical resolution of corresponding TIR CO_2 profile by~~We then~~ applying~~ied~~ TIR CO_2 averaging kernel functions (AK) to the CME_obs. profile, as follows (Rodgers and Connor, 2003):

$$\mathbf{x}_{\mathbf{CME\_AK}} = \mathbf{x}_{\mathbf{a\ priori}} + \mathbf{A}\left(\mathbf{x}_{\mathbf{CME\_obs.}} - \mathbf{x}_{\mathbf{a\ priori}}\right). \qquad (1)$$

Here, $\mathbf{x}_{\mathbf{CME\_obs.}}$ and $\mathbf{x}_{\mathbf{a\ priori}}$ are the CME_obs. and a priori CO_2 profiles, respectively. CME_obs. data with TIR CO_2 averaging kernels was designated as "CME_AK", as indicated by the blue line in Figure 3(a).

We set two different criteria for the time difference between TANSO-FTS TIR and CME CO_2 profiles used for selection of coincident pairs: a 24-h difference and a 72-h difference. Figure 4 shows a comparison of the results over Narita a~~A~~irport for coincident pairs with a 24- or 72-h time difference. Both averages and 1-σ standard deviations of differences between TIR and CME CO_2 data selected using the 24- and 72-h thresholds were comparable, as shown in Figure 4, which means that the use of these two time difference criteria does not alter any conclusions drawn from comparisons of TIR and CME CO_2 data. The same was generally applied generally to comparisons over the other airports shown in Figure 1. Hence, we adopted a 72-h time difference between TIR and CME CO_2 measurement times for selecting coincident pairs to increase the number of pairs available.

We selected coincident pairs of TIR and CME_AK CO_2 profiles by applying the thresholds of a 300-km distance and a 72-h time difference and calculated the difference in CO_2 concentrations (TIR minus CME_AK) for each retrieval grid layer. All the airports we used were then divided into four latitude bands (40°S−20°S, 20°S−20°N, 20°N−40°N, and 40°N−60°N), and average differences were calculated for each latitude band, retrieval layer, and season (northern spring, MAMN; northern summer, JJA; northern fall, SON; and northern winter, DJF). The signs of the calculated average differences were flipped and defined as "bias-correction values" for the 28 retrieval grid layers, four latitude bands, and four seasons. The numbers of coincident pairs of TIR and CME_AK CO_2 profiles varied depending on latitude band and season. The largest number of coincident pairs was obtained in the latitude band of 20°N−40°N including Narita airport, where 506−2501 pairs were obtained. 63−310 and 77−472 coincident pairs were obtained at 40°S−20°S and 40°N−60°N, respectively. The comparison area for low latitudes was extended to a band of 20°S−20°N, because the number of coincident pairs in that region was smaller (0−341) than in other latitude bands; nevertheless, there were no coincident pairs at 20°S−20°N in the JJA seasons of 2011 and 2012. The number of coincident pairs was smallest (0−30) at 20°S−0° and at 20°S−0°; no data were collected there after September 2010. Thus, all bias-correction values for 20°S−20°N after the SON season of 2010 were determined based on data from 0°−20°N.

4.2 Comparison of TIR CO_2 data with NICAM-TM CO_2 data

In this study, we compared monthly averaged TANSO-FTS TIR and NICAM-TM CO_2 data. We used 2.5° grid data from NICAM-TM glevel-5 CO_2 simulations, and calculated monthly averaged TIR and NICAM-TM CO_2 data for each of these 2.5° grids. Here, we interpolated the NICAM-TM CO_2 data from 40 vertical levels into CO_2 concentrations at the 28 retrieval grid layers of TIR CO_2 data. Besides TIR CO_2 data, a priori CO_2 data and TIR CO_2 averaging kernel functions data were also averaged for each month and each 2.5° grid. For each of the 2.5° grids, we applied the monthly averaged TIR CO_2 averaging kernel functions to the corresponding monthly averaged NICAM-TM CO_2 profiles using expression (1) with the corresponding monthly averaged a priori CO_2 profiles. We then calculated differences in CO_2 concentrations between monthly averaged TIR data and monthly averaged NICAM-TM data with TIR averaging kernel functions for each grid. Here, two types of differences were calculated between TIR CO_2 data and NICAM-TM CO_2 data with TIR CO_2 averaging kernel functions: (1) the difference with respect to the original TIR CO_2 data and (2) the difference with respect to bias-corrected TIR CO_2 data to which the bias-correction values described above were applied.

TIR CO_2 averaging kernel functions depend on TIR measurement spectral noise, a priori CO_2 profile variability, and CO_2 Jacobians. Of these three parameters, covariance matrices of the TIR measurement noise and a priori CO_2 profile were set in the same manner for all TIR V1 L2 CO_2 data (Saitoh et al., 2016). The CO_2 Jacobians depend on temperature and CO_2 profiles, and therefore change with location and time. However, TIR CO_2 averaging kernel functions showed nearly identical structures with each other when collected for each 2.5° grid in one month, which means that applying the monthly averaged TIR CO_2 averaging kernel functions did not affect the conclusions of this study.

5. Results

5.1 Bias of TIR LT and MT CO_2 concentrations

Figure 5 presents a comparison between TANSO-FTS TIR V1 and CME_AK CO_2 profiles over Narita aAirport in each season in 2010. In all seasons, TIR CO_2 data in the LT and MT regions had negative biases against CME_AK CO_2 data. The largest negative biases in TIR CO_2 data were found in the MT region centered at 500−400 hPa. The peak of the negative biases in spring and summer occurred at ~400 hPa, slightly higher than the peak pressure level in fall and winter (~500 hPa), which corresponds to the pressure level at which the TIR CO_2 averaging kernels exhibited their highest sensitivity in each season. Saitoh et al. (2016) showed that TIR V1 CO_2 data agreed well with CME level flight CO_2 data in the UT region (287−196 hPa) corresponding to retrieval layers 9 and 10. As indicated by the solidthick black lines in Figure 5, the negative biases in the TIR CO_2 data against CME ascending and descending flight CO_2 data decreased as altitude increased, which is consistent with the results of Saitoh et al. (2016).

Figure 6 shows differences between TANSO-FTS TIR V1 and CME_AK CO_2 data in the LT and MT regions in retrieval layers 3–8 for each latitude band and each season. TIR CO_2 data had consistent negative biases of 1−1.5% against CME_AK CO_2 data in all retrieval layers from 736 to 287 hPa3 to 8, with the largest negative biases at in retrieval layers 5–6 (541−398 hPa (retrieval layers 5−6)) for all latitude bands and seasons, except for 40°S−20°S in the DJF seasons of 2011 and 2012. Here, we have omitted a detailed discussion of TIR CO_2 data at pressure levels below 736 hPain (retrieval layers 1− and 2 (< 736 hPa), because TIR measurements have relatively low sensitivity to CO_2 concentrations in these layers, as shown in Figure 3(b). The largest negative biases, up to 7.3 ppm, existed in low latitudes during the JJA season, as indicated by the red line in the upper panel of Figure 6(b), while there were no coincident pairs of TIR and CME CO_2 data in the same season of 2011 and 2012. As presented in Table 2, tThe negative biases in TIR CO_2 data were larger in spring (MAM) and summer (JJA) than in fall (SON) and winter (DJF) in northern middle latitudes (20°N−40°N), as was the case for UT comparisons presented in Saitoh et al. (2016). On a global scale, the seasonality of negative biases was not clear, given the relatively large 1-σ standard deviations (horizontal bars in the top panels of Figure 6), although these biases tended to be larger in the spring hemisphere than in the fall hemisphere within each latitude band. Comparing results among the three years, the negative biases in TIR CO_2 data slightly increased over time in some latitude bands and seasons, but not as sharply as in the UT CO_2 comparisons discussed in Saitoh et al. (2017). Note that the number of comparison pairs used in Figure 6 varied among latitude bands; the largest number occurred at 20°N−40°N, which includes Narita aAirport, Japan, and the number of coincident profiles decreased in low latitudes and the Southern Hemisphere, where there are fewer airports.

5.2 Validity of bias correction based on CME data

Negative biases in TANSO-FTS TIR V1 CO_2 data in the LT and MT regions did not exhibit evident dependence on season or year, as shown in Figure 6. However, it is difficult to discern whether bias assessment using TIR CO_2 data over airports reflects the typical features of each latitude band due to the limited airport locations. Therefore, we validated the applicability of the bias-correction values based on comparisons with CME_AK CO_2 data over the entire area of each latitude band by comparing TIR CO_2 data to NICAM-TM CO_2 data to which TIR CO_2 averaging kernel functions were applied on a global scale. Figure 7 shows the frequency distributions of differences in monthly averaged CO_2 concentrations between TIR and NICAM-TM CO_2 data in all retrieval layers from 736 to 287 hPa in all 2.5° grids over the latitude range of 40°S to 60°N. As shown by the dashed lines in Figure 7, the mode values of the frequency distributions generally corresponded to the median values, indicating that TIR CO_2 data did not have locally distorted biases against NICAM-TM CO_2 data. In addition, negative biases of TIR CO_2 data against NICAM-TM CO_2 data in all seasons slightly increased ~~by 1 ppm or less per year~~ over time~~in all seasons~~, judging from the mode values presented in the top left boxes of Table 3, although the increase in negative biases was not much~~also~~ evident as in the comparisons over airports shown in Figure 6; this may be partly because of slightly high growth rate of NICAM-TM simulations (2.4 ppm/yr) compared to in-situ observations (2.2 ppm/yr).

The solid~~thick~~ lines in Figure 7 show frequency distributions of differences between NICAM-TM CO_2 data and bias-corrected TIR CO_2 data to which the bias-correction values defined for each retrieval layer, latitude band, and season were applied. The mode values presented in the top right boxes of Table 3, which were nearly identical to the median values, were closer to zero in all three years. In addition, variability in the differences, as indicated by the width of the distribution, between bias-corrected TIR and NICAM-TM CO_2 data was comparable to or smaller than that between the original TIR and NICAM-TM CO_2 data; this can be seen by comparisons in values of frequencies at the mode values between before and after applying the bias-corrections values, presented in Table 3. This demonstrates the validity of the 288 bias-correction values defined for six retrieval layers ~~(3−8~~from 736 to 287 hPa~~)~~, four latitude bands (0°S−20°S, 20°S−20°N, 20°N−40°N, and 40°N−60°N), and four seasons of 2010−2012. We thus conclude that the bias-correction values defined based on comparisons in limited areas near airports are generally applicable to TIR CO_2 data in areas other than the airport locations. However, there were some exceptions during the JJA season. As indicated by the solid~~thick~~ black line in Figure 7(c), the frequency distribution of differences between bias-corrected TIR and NICAM-TM CO_2 data in the JJA season of 2010 had a clear bimodal feature, with one of the mode values located near 4 ppm.

We divided the frequency distribution in the JJA season of 2010 into three categories based on the retrieval layers: 736−541 hPa (retrieval layers 3−4), 541−398 hPa (retrieval layers 5−6), and 398−287 hPa (retrieval layers 7−8), as shown in Figure 8. A frequency distribution with a mode of 4 ppm was obtained from bias-corrected TIR CO_2 data in the MT region above 541 hPa~~retrieval layer 5~~, especially on ~~in retrieval layers~~ 398~~7~~−287 hPa~~8~~. That is, TIR CO_2 data on 398−287 hPa ~~in retrieval layers 7−8~~ in the JJA season of 2010 were clearly overcorrected when applying the bias-correction values defined in this study. In the retrieval layers of 736−541 hPa~~In retrieval layers 3−4~~, the mode value of the frequency distribution after bias-correction was close to zero and the width of the distribution narrowed, demonstrating the validity of the corresponding bias-correction value. For the JJA seasons of 2011 and 2012, bias-correction values could not be determined because there were no coincident pairs between TIR and CME CO_2 data over airports; therefore, we substituted the bias-correction value for the same season of 2010. The frequency distribution of the differences between NICAM-TM and TIR CO_2 data after bias-correction in the JJA season of 2011 had a somewhat bimodal shape, while that in the JJA season of 2012 did not have any bimodal structure, as shown in Figure 7(c). The negative bias of the original TIR CO_2 data against NICAM-TM CO_2 data in the JJA season of 2012 was larger than that in the JJA season of 2010; thus, applying the bias-correction value for 2010 to the 2012 TIR CO_2 data did not lead to any evident overcorrection.

Next, we divided the frequency distribution in the retrieval layers of 398~~7~~−287 hPa~~8~~ in the JJA season of 2010, shown in Figure 8, into four latitude bands. Judging from the results presented in Figure 9, overcorrection of the negative biases in TIR CO_2 data against NICAM-TM CO_2 data occurred at 20°S−20°N and 40°N−60°N; TIR CO_2 data were markedly overcorrected by the bias-correction value based on comparisons of CME CO_2 data over airports, especially in the latitude band of 20°S−20°N. As shown in the upper panel of Figure 6, negative biases in TIR CO_2 data against CME CO_2 data over airports in low latitudes during the JJA season were clearly larger than the biases found in other latitudes and seasons. Judging from comparisons of global NICAM-TM CO_2 data, however, applying bias-correction values based on the negative biases observed over airports to TIR CO_2 data over the entire area of 20°S−20°N led to overcorrections in most cases.

6. Discussion

Any uncertainties in a priori data can affect retrieval results. A priori CO_2 data taken from the NIES-TM05 model (Saeki et al., 2013b) was used in the TANSO-FTS TIR V1 CO_2 retrieval processing, and exhibited consistent negative biases against CME CO_2 data in the troposphere and the lower stratosphere~~retrieval layers 3−8~~. As discussed in Saitoh et al. (2016), the negative biases in a priori CO_2 data were one likely reason for negative biases in retrieved CO_2 concentrations in the UTLS region. The same pattern holds for negative biases in TIR CO_2 data in the LT and MT~~L~~ regions. However, negative biases in retrieved TIR CO_2 data were larger than those of a priori CO_2 data in the LT and MT regions, as shown in Figure 5. Furthermore, the vertical and latitudinal structures of the negative biases in TIR CO_2 data did not always correspond to those in a priori CO_2 data. Although negative biases in a priori CO_2 data surely contribute to negative biases in TIR V1 CO_2 data in the LT and MT regions, there are likely other considerable sources of TIR CO_2 negative biases.

Uncertainty in atmospheric temperature data could affect CO_2 retrievals. As shown in Figure 7(a) of Saitoh et al. (2009), uncertainties in retrieved CO_2 concentrations due to uncertainties in atmospheric temperature were largest in the UT, upper MT, and LT regions; a bias of 1 K in atmospheric temperature can yield up to ~10% uncertainty in retrieved CO_2 concentrations in the MT and LT regions. However, simultaneous retrieval of atmospheric temperature in the V1 CO_2 retrieval algorithm could decrease the effect on CO_2 retrieval results. In addition to that, no evidence has been reported that the JMA-GPV temperature data used as initial values (equal to a priori values) in the TIR V1 CO_2 retrieval processing ha~~ved~~ biases over such wide latitudinal areas, as in this study. Thus, uncertainty in atmospheric temperature is not a primary cause of negative biases in TIR CO_2 data in the LT and MT regions. Although the effect of uncertainty in H_2O data on CO_2 retrieval results could be also decreased by simultaneous retrieval of H_2O with CO_2 in the TIR V1 algorithm, water vapor is abundant in the tropics, so that we cannot deny the possibility of its effect on CO_2 retrieval results. Similarly, error in the judgement of cloud contamination in low latitudes with high cloud occurrence frequency may affect CO_2 retrieval results.

As shown in Figure 6, the largest negative biases in TIR V1 CO_2 data existed in the MT region in low latitudes (20°S−20°N) during the JJA season. Degrees of freedom (DF) of TIR V1 CO_2 data were highest in low latitudes, exceeding 2.2 in all seasons, which means retrieved CO_2 concentrations there contained more information coming from TANSO-FTS TIR L1B spectra and thus were relatively less constrained to a priori concentrations.

Kataoka et al. (2014) reported biases in TANSO-FTS TIR V130.131 L1B radiance spectra, which were a previous version of the V161 L1B data used in TIR V1 L2 CO_2 retrieval, on the basis of a double difference method. Similar analysis for the V161 L1B spectra is in progress. Kuze et al. (2016) summarized updates in the processing method for TANSO-FTS L1B spectra and~~. They~~ showed that the V161 and newer version (V201) of TANSO-FTS L1B spectra still had~~ve~~ considerable uncertainties via theoretical simulations. ~~As shown in Figure 6, the largest negative biases in TIR V1 CO_2 data existed in the MT region in middle and low latitudes during spring and summer, where TANSO-FTS TIR measurements have relatively large sensitivity to CO_2 concentrations and thus the retrievals are less constrained to a priori concentrations.~~Kataoka et al. (2014) and Kuze et al. (2016) demonstrated that TANSO-FTS TIR L1B spectra had considerable radiance biases, which were largest at around 15-μm CO_2 absorption band.

~~This implies that biases in L1B spectra are a major cause of the negative biases in retrieved CO_2 concentrations, as Saitoh et al. (2016) noted in the UT region.~~ In the TIR V1 CO_2 retrieval algorithm, we simultaneously retrieved surface temperature and surface emissivity with CO_2 concentration as a correction parameter for radiance biases in the V161 spectra, as explained in Saitoh et al. (2016). In the CO_2 retrieval, these surface parameters were retrieved to correct the radiance~~spectral~~ biases separately in the three spectral regions of the 15-μm (690−715 cm^{-1}, 715−750 cm^{-1}, and 790−795 cm^{-1}), 10-μm (930−990 cm^{-1}), and 9-μm bands (1040−1090 cm^{-1}). As reported in Saitoh et al. (2016), the simultaneous retrieval of surface parameters for correction of radiance~~spectral~~ biases increased the number of normally retrieved CO_2 data (by roughly 1.5 times over Narita a~~A~~irport). This demonstrates a certain level of validity for the correction of radiance~~spectral~~ biases through simultaneous retrieval of surface parameters for the V161 spectra. However, we note that retrieving surface parameters for radiance~~spectral~~ bias correction at each wavelength band may affect retrieved CO_2 concentrations, and remaining radiance~~spectral~~ biases after correction at each wavelength band may also affect retrieved CO_2 concentrations.

To examine the effect of the simultaneous retrieval of surface parameters at each of the three wavelength bands on retrieved CO_2 concentrations, ~~The V1 CO_2 retrieval algorithm utilized 15-μm, 10-μm, and 9-μm bands. Here,~~ we performed test retrievals of CO_2 concentrations using V161 spectra in four cases: using all three of these bands, in the same manner as the V1 algorithm; using two bands, 15-μm and 10-μm; using two bands, 15-μm and 9-μm; and using the 15-μm band only.

Figure 10 shows the CO_2 retrieval results for two~~three~~ TANSO-FTS observations~~,~~ over Narita airport in April 2010~~in low latitudes during summer and in northern middle latitudes in spring, where most TIR V1 CO_2 data had negative biases~~. As shown~~indicated by the black lines~~ in Figure 10(a), negative biases in TIR CO_2 concentrations against nearby CME CO_2 concentrations in the LT and MT regions became notably smaller when using the 15-μm and 9-μm bands (black dashed line~~s~~) and the 15-μm band only (black dashed-dotted line~~s~~), both conditions that did not use the 10-μm band. It is clear that using the 9-μm band did not contribute to negative biases in retrieved CO_2 concentrations, judging from the minor difference in CO_2 concentrations between the use of all three bands (solid~~thick~~ line~~s~~) and the use of the 15-μm and 10~~9~~-μm bands (dotted line~~s~~). In addition, there were no major differences in retrieved CO_2 concentrations among the four retrieval cases when the original V1 CO_2 profile did not have distinct negative biases, as shown ~~illustrated by the gray lines~~ in Figure 10(b). According to theoretical calculations shown in Figure 13 in Kuze et al. (2016), there were no distinct radiance biases in the 10-μm band in the latest version of the TANSO-FTS TIR spectra. If it is true for observed TIR radiances, our test retrievals imply that simultaneous retrieval of surface parameters for TIR spectra at the 10-μm band with less radiance bias worsened CO_2 retrieval results. T~~From t~~he~~se~~ test retrieval results demonstrate that~~, we conclude that~~ using the 10-μm band in conjunction with the 15-μm and 9-μm bands in the V1 retrieval algorithm is a probable cause of the negative biases in retrieved CO_2 concentrations in the LT and MT regions, although this cannot fully explain the biases.~~.~~

CO_2 absorption at 15 μm is considerably larger than that at 9 or 10 μm. However, measurements in the 9-μm and 10-μm bands are most sensitive to CO_2 concentrations in the LT and MT regions; the peak sensitivity of the 9-μm and 10-μm bands occurred on~~in retrieval layers~~ 736~~3~~−541 hPa~~4~~ and 541~~5~~−398 hPa~~6~~, respectively, judging from CO_2 Jacobian values. Therefore, using the 9-μm and 10-μm bands in conjunction with the 15-μm band should be useful for retrieving CO_2 vertical profiles. In fact, in the case of the retrieval result ~~low latitudes in summer~~ shown in Figure 10(a), the degree of freedom of CO_2 retrieval was 1~~2~~.93~~08~~ when using the 15-μm band only, and it increased to 1~~2~~.94~~09~~, 1.95~~2.11~~, and 1.96~~2.12~~ when adding the 9-μm band, the 10-μm band, and both the 9-μm and 10-μm bands, respectively.~~ According to Figure 13 in Kuze et al. (2016), there was no distinct uncertainty in the 10-μm band in the latest version of the TANSO-FTS TIR spectra. Our test retrievals imply that simultaneous retrieval of surface parameters for the 10-μm band over- or under-corrected the spectral bias of V161 spectra.~~ In the next update of the CO_2 retrieval algorithm for TANSO-FTS TIR spectra, we should consider an improved method for correcting radiance~~spectral~~ biases in CO_2 retrieval processing or adopting the correction of TIR L1B spectra themselves proposed by Kuze et al. (2016).

Bias-correction values determined based on comparisons of CME CO_2 data over airports overcorrected negative biases in TIR CO_2 data in the upper MT region from 398 to 287 hPa~~(layers 7−8)~~ in low latitudes (20°S−20°N) during the JJA season, as shown in Figure 9. The CME data that determined the bias-correction values of the 20°S−20°N latitude band were concentrated in Southe~~E~~ast Asia, as illustrated in Figure 1: BKK (Bangkok), SIN (Singapore), and CGK (Jakarta). In addition, the bias-correction values for the 20°S−20°N latitude band after the SON season of 2010 were determined from comparisons of CME data at 0°−20°N, because no data were collected at 20°S−0° after September 2010, as mentioned above. Figure 11 shows differences between TIR CO_2 data with no bias correction and NICAM-TM CO_2 data with TIR CO_2

averaging kernel functions on 682 hPa~~in retrieval layers 3~~ and 314 hPa~~8~~ in July 2010. As shown in the lower panel of Figure 11, ~~In most areas of retrieval layer 8 at 0°−20°N,~~ TIR CO_2 data on 314 hPa had negative biases against NICAM-TM CO_2 data in most areas at 0°−20°N,~~,~~ and the negative biases were largest near airport locations in Southe~~E~~ast Asia. At 20°S−0°, on the other hand, TIR CO_2 data~~ in retrieval layer 8~~ on 314 hPa were closer to NICAM-TM CO_2 data than at 0°−20°N. Relying on NICAM-TM CO_2 data, which incorporates CONTRAIL CO_2 data in the inversion, application of bias-correction values determined mainly from comparisons of CME CO_2 data in the MT region at 0°−20°N to TIR CO_2 data over the entire area of low latitudes including 20°S−0° produced widespread overcorrection.

In general, there are few areas where we can obtain reliable in situ CO_2 data for validation analysis. In particular, there are very few in situ CO_2 data in the free troposphere where TIR observations are most sensitive, compared to the surface. In low latitudes, there are relatively strong updrafts, and thus there are larger uncertainties among models than in other areas due to differences in the parameterization of vertical transport. Therefore, a priori CO_2 concentrations taken from the NIES-TM05 model (Saeki et al., 2013b) probably have larger uncertainties in the MT region in low latitudes. As retrieved TIR CO_2 concentrations were to some extent constrained by a priori concentrations, they possibly had more~~In retrieval from TIR spectra, the more atmospheric layers in which we retrieve CO_2 concentrations, the lower the information content of the retrieval result in each layer becomes; as a result, the retrieved concentrations are constrained by a priori model data. Thus, there is a high possibility of~~ ~~large~~ biases attributed to the a priori uncertainties in the MT region~~retrieved TIR CO_2 concentrations~~ in low latitudes. More in-situ CO_2 data in the upper atmosphere in low latitudes are needed to validate both satellite data and model results. Although HIAPER Pole-to-Pole Observations (HIPPO) data (Wofsy et al., 2011) are not suitable for a comprehensive validation study as in this study due to their limited observation periods, HIPPO CO_2 data are useful to validate CO_2 vertical profiles observed by satellite-borne sensors and simulated in models (Kulawik et al., 2013). In addition, there may also be large biases in retrieved CO_2 data in local source and sink regions, where model data are more variable depending on the surface flux dataset. In such areas, it is difficult to determine bias-correction values that can be applicable over a vast area; it is true in the case of 40°N−60°N. In conclusion, comprehensive validation analysis of satellite data is still needed to evaluate accuracy both in background regions and in regions with high CO_2 variability. Reconsideration of the setting of retrieval grid layer~~s grid~~ is also needed so that measurement information should be included more prominently in TIR CO_2 retrieval results.

Overall, the bias-correction values evaluated in each retrieval layer, latitude band, and season (Figure 6) can be applied to corresponding TIR CO_2 data, except at 20°S−20°N during the JJA seasons of 2011 and 2012~~1~~, when bias-correction values were not determined due to a lack of coincident CME CO_2 data. In these two cases, we recommended applying bias-correction value 0.5 ppm and 1.0 ppm larger than the corresponding bias-correction value for 2010 to TIR CO_2 data for 2011 and 2012, respectively, judging from comparison results between the original TIR and NICAM-TM CO_2 data.

7. Summary

We evaluated biases of the GOSAT/TANSO-FTS TIR V1 L2 CO_2 product in the LT and MT regions (736–287 hPa) by comparing the TIR CO_2 profiles with coincident CONTRAIL CME CO_2 profiles over airports from 2010 to 2012. Coincident criteria for comparisons of a 300-km distance and a 72-h time difference yielded a sufficient number of coincident pairs, except in low latitudes (20°S−20°N) during JJA seasons of 2011 and 2012. Comparisons between TIR CO_2 profiles and CME CO_2 profiles to which TIR CO_2 averaging kernel functions were~~had been~~ applied showed that the TIR V1 CO_2 data had consistent negative biases of 1−1.5% against CME CO_2 data in the LT and MT regions; the negative biases were the largest on 541−398 hPa (~~in~~ retrieval layers 5−6~~ (541−398 hPa~~), and were larger in spring and summer than in fall and winter in northern middle latitudes, as is the case in the UT region (287−196 hPa). Our test retrieval simulations showed that using the 10-μm CO_2 absorption band (930−990 cm^{-1}), in addition to the 15-μm (690−750 cm^{-1} and 790−795 cm^{-1}) and 9-μm (1040−1090 cm^{-1}) bands, increased~~probably caused these~~ negative biases in retrieved CO_2 concentrations in the LT and MT regions, suggesting that simultaneous retrieval of surface parameters for radiance bias correction at the 10-μm band worsene~~over- or under-correcte~~d CO_2 retrieval results.~~the spectral biases inherent to TANSO-FTS V161 L1B spectra.~~

We then performed global comparisons between TIR V1 CO_2 data and NICAM-TM CO_2 data with considering TIR CO_2 averaging kernel functions to confirm the validity of the bias assessment over airports. Differences in CO_2 concentrations between TIR and NICAM-TM data approached an average of zero after application of the bias-correction values to TIR CO_2 data, demonstrating that the bias-correction values evaluated over airports in limited areas are applicable to TIR CO_2 data for the entire areas of 40°S–60°N. Note that applying the bias correction value at 20°S–20°N in the upper MT region (398−287 hPa) during the JJA season resulted in overcorrection of TIR CO_2 data.

This study presented bias-correction values for the GOSAT/TANSO-FTS TIR V1 L2 CO_2 product evaluated in the LT and MT region (~~for retrieval layers~~ 7363−287 hPa)8 in each latitude band and each season of 2010−2012. This information should be useful for further analyses, including CO_2 surface flux estimation and transport process studies using TIR CO_2 data in the free troposphere, and also helpful for evaluating wavelength-dependent radiance~~spectral~~ biases in TANSO-FTS TIR spectra to improve TIR CO_2 retrieval algorithm~~ for the TIR spectra~~.

Data availability

GOSAT/TANSO-FTS TIR V1 L2 and a priori NIES-TM05 CO_2 data and TIR CO_2 averaging kernel data are available at http://www.gosat.nies.go.jp/en/. Contact the CONTRAIL project (http://www.cger.nies.go.jp/contrail/index.html) to access CONTRAIL CME CO_2 data. Contact Y. Niwa for detailed information on NICAM-TM CO_2 simulations. Contact the corresponding author, N. Saitoh, to obtain the table of bias-correction values for TIR V1 L2 CO_2 data evaluated in this study.

Acknowledgment.

We thank all the members of the GOSAT Science Team and their associates. We are also grateful to the engineers of Japan Airlines, the JAL Foundation, and JAMCO Tokyo for supporting the CONTRAIL project. This study was funded by the Japan Aerospace Exploration Agency (JAXA). This study was performed within the framework of the GOSAT Research Announcement.

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Table 1. Pressure levels of retrieval grid layers of GOSAT/TANSO-FTS TIR V1 L2 CO_2 data focused on in this study.

Layer level	Pressure level of each layer (hPa)	Lower pressure level (hPa)	Upper pressure level (hPa)
1	927.79	1165.91	857.70
2	795.08	857.70	735.64
3	682.10	735.64	630.96
4	585.63	630.96	541.17
5	502.47	541.17	464.16
6	430.97	464.16	398.11
7	369.64	398.11	341.45
8	314.23	341.45	287.30
9	262.10	287.30	237.14
10	216.36	237.14	195.73

Table 2. Biases of GOSAT/TANSO-FTS TIR CO_2 data against CME_AK CO_2 data in each season of 2010−2012 at 541−464 hPa (left side of each box) and at 464−398 hPa (right side of each box) where the largest biases occurred in most cases. 541−464 and 464−398 hPa correspond to retrieval layers 5 and 6, respectively. Biases could not be evaluated due to no coincident data in the JJA seasons of 2011 and 2012.

DJF / MAM JJA / SON	40°S−20°S		20°S−20°N		20°N−40°N		40°N−60°N	
2010	-2.1/-2.5	-1.1/-1.6	-4.1/-3.9	-4.5/-3.8	-4.2/-3.9	-5.1/-5.1	-4.1/-4.1	-6.0/-5.8
	-2.1/-2.4	-4.9/-4.7	-7.0/-7.3	-4.2/-4.3	-4.3/-4.6	-3.2/-3.4	-5.0/-5.0	-3.6/-4.1
2011	-1.7/-2.9	-4.2/-4.1	-4.6/-4.2	-4.7/-4.6	-3.9/-3.7	-5.3/-5.4	-4.5/-4.8	-5.2/-5.1
	-3.3/-3.4	-5.7/-5.4	−	-5.6/-5.5	-5.1/-5.7	-3.2/-3.3	-4.4/-4.6	-3.3/-3.9
2012	-2.2/-3.1	-2.9/-3.4	-3.9/-3.9	-5.6/-5.7	-3.9/-3.8	-5.8/-5.9	-4.3/-4.6	-5.3/-5.5
	-4.9/-4.9	-5.3/-5.5	−	-5.9/-5.7	-5.8/-6.3	-5.2/-4.9	-6.4/-6.5	-6.4/-6.7

Table 3. Mode values of frequency distributions of differences in monthly averaged CO_2 concentrations between original (top left boxes) or bias-corrected (top right boxes) GOSAT/TANSO-FTS TIR and NICAM-TM CO_2 data in each season of 2010−2012, shown in Figure 7. The mode values presented here indicate the center value of a bin with a width of 0.5 ppm; a bin of “0.0” ranges from -0.25 to +0.25 ppm. Ratios of numbers of data categorized into each of the mode values to numbers of all 2.5° gridded data for comparisons (bottom boxes) are shown in middle left (original) and right (bias-corrected) boxes.

	DJF [original]	DJF [bias-corrected]	MAM [original]	MAM [bias-corrected]	JJA [original]	JJA [bias-corrected]	SON [original]	SON [bias-corrected]
2010 mode value (ppm)	-2.0	0.5	-2.5	0.0	-2.5	0.0	-2.5	0.5
2010 frequency (%)	13.6	13.9	10.5	12.9	10.7	10.4	11.8	11.1
2010 number of all 2.5° gridded data	641,427		947,983		1,176,998		1,279,370	
2011 mode value (ppm)	-3.0	0.5	-3.5	1.0	-2.5	1.0	-2.5	0.5
2011 frequency (%)	11.3	12.1	8.8	11.4	9.8	9.4	11.5	9.4
2011 number of all 2.5° gridded data	1,156,444		1,093,808		1,156,010		1,222,288	
2012 mode value (ppm)	-3.0	0.0	-4.0	0.0	-3.5	1.0	-4.0	0.5
2012 frequency (%)	12.1	13.1	8.7	11.8	9.3	10.5	10.6	10.5
2012 number of all 2.5° gridded data	1,050,530		1,010,457		1,148,979		1,117,909	

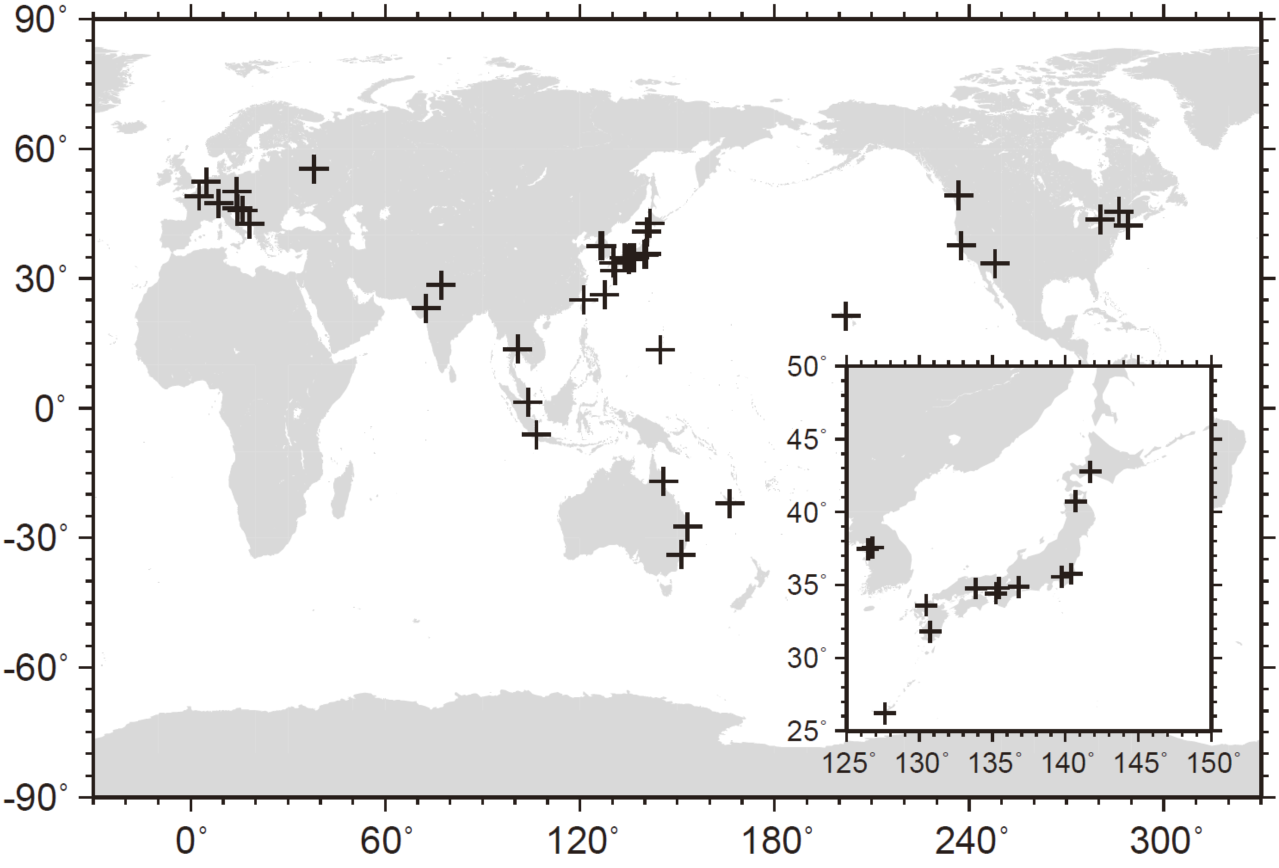


Figure 1. Locations of airports at which CONTRAIL CME ascending and descending observations were collected used in~~for~~ this study.

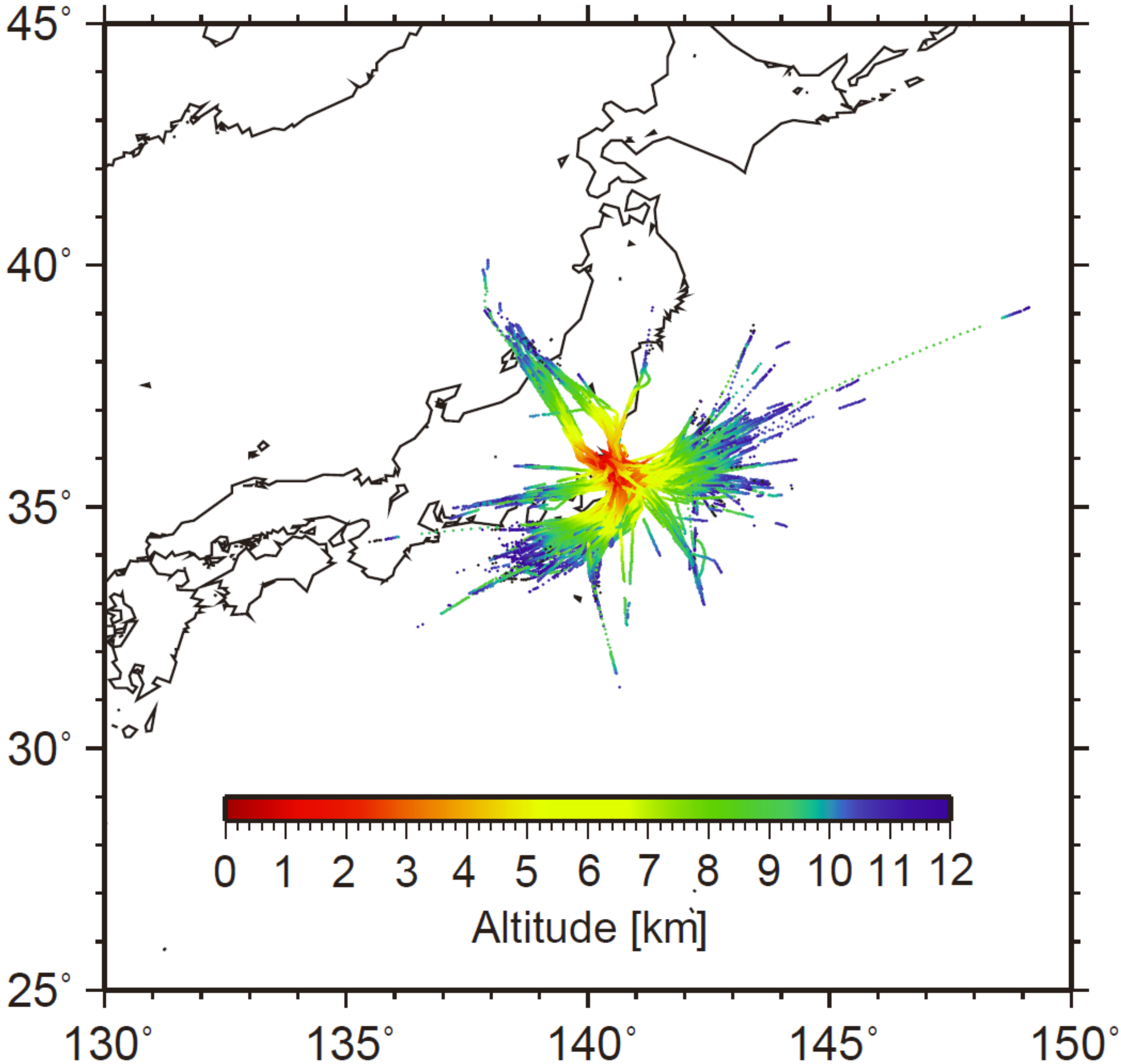
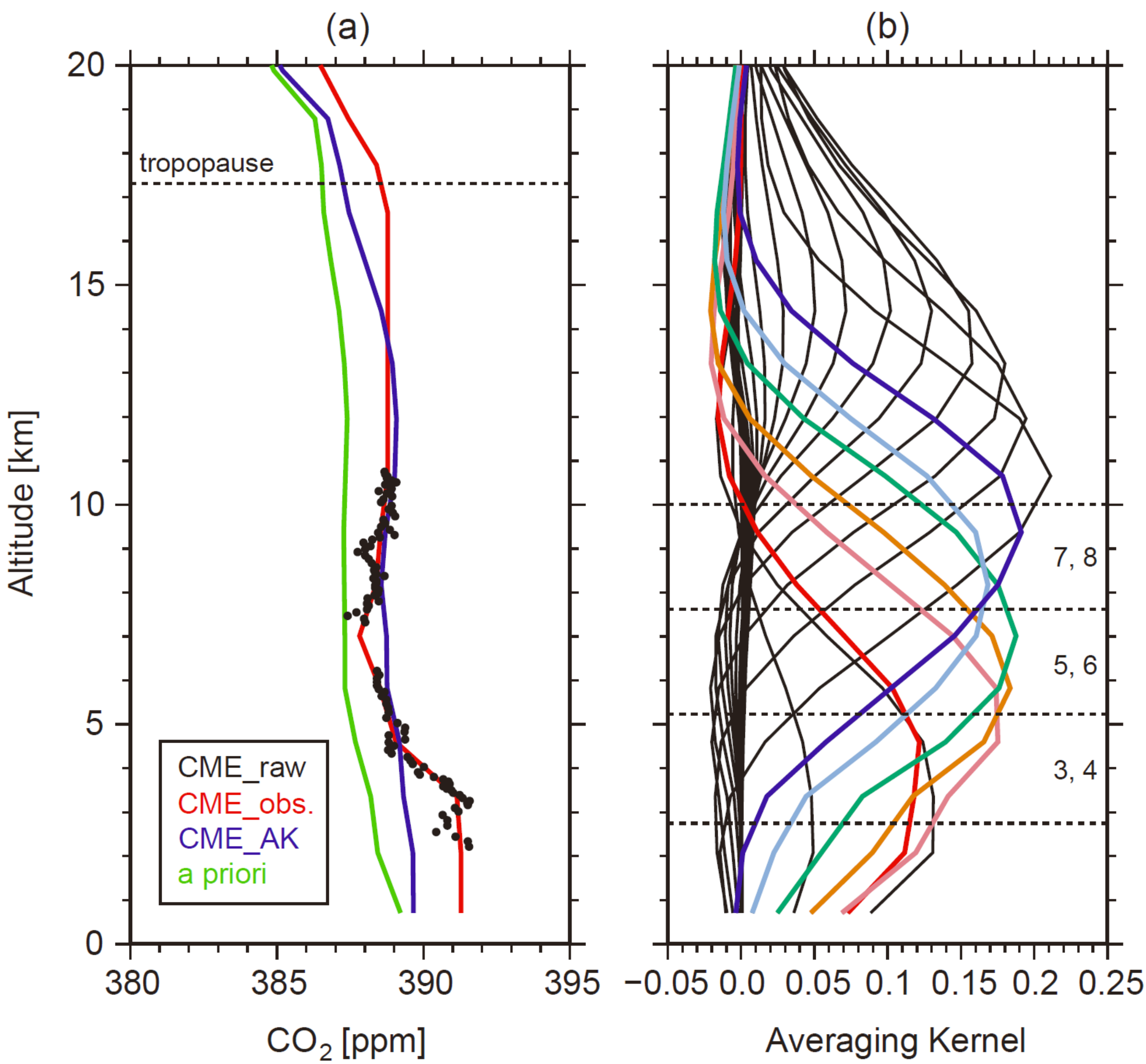


Figure 2. Flight tracks of all CME ascending and descending observations over Narita airport in 2010. Color indicates the altitude levels of each flight.



(a)
(b)
tropopause
CME_raw
CME_obs.
CME_AK
a priori
Altitude [km]
CO2 [ppm]
Averaging Kernel
7, 8
5, 6
3, 4

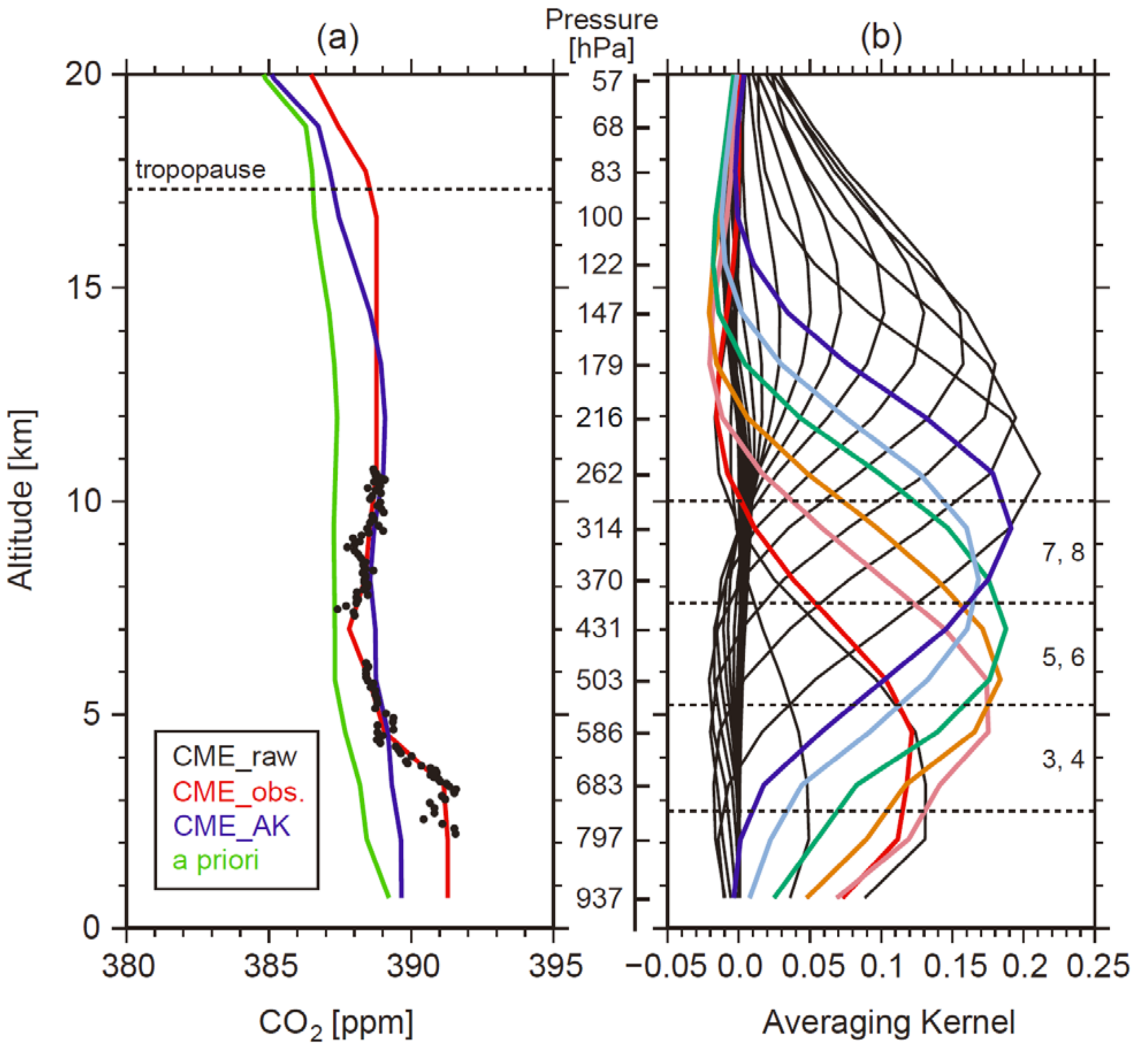
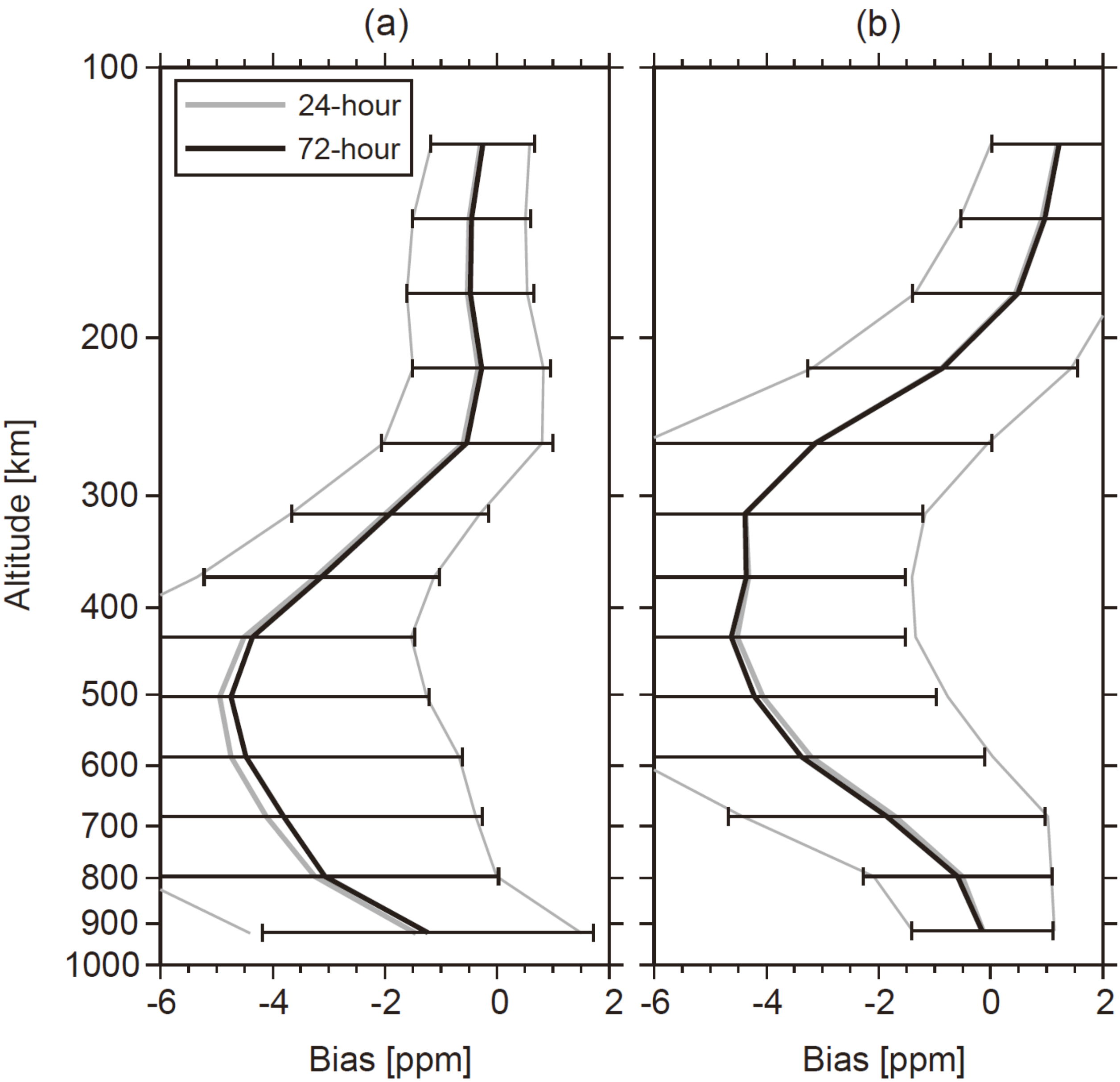


Figure 3. (a) Black circles represent original CME data (CME_raw), the red line shows an interpolated profile of the CME data into GOSAT/TANSO-FTS TIR CO_2 28 retrieval grid layers (CME_obs), ~~and~~ the blue line shows the interpolated profile to which TIR averaging kernel functions, shown in panel (b), are applied (CME_AK), and the green line shows a priori CO_2 profile.


(a)
(b)
24-hour
72-hour
Altitude [km]
100
200
300
400
500
600
700
800
900
1000
-6
-4
-2
0
2
Bias [ppm]

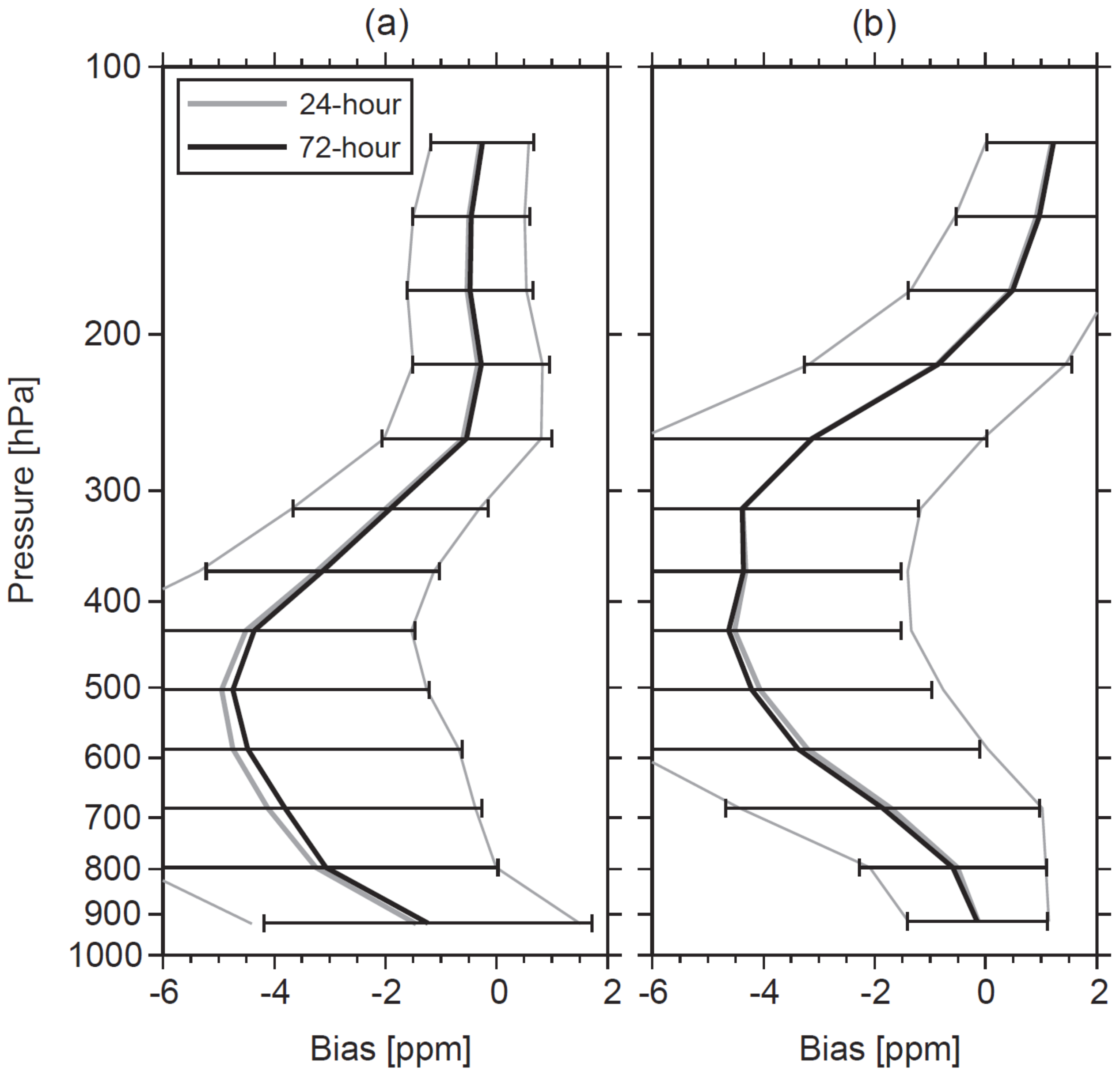
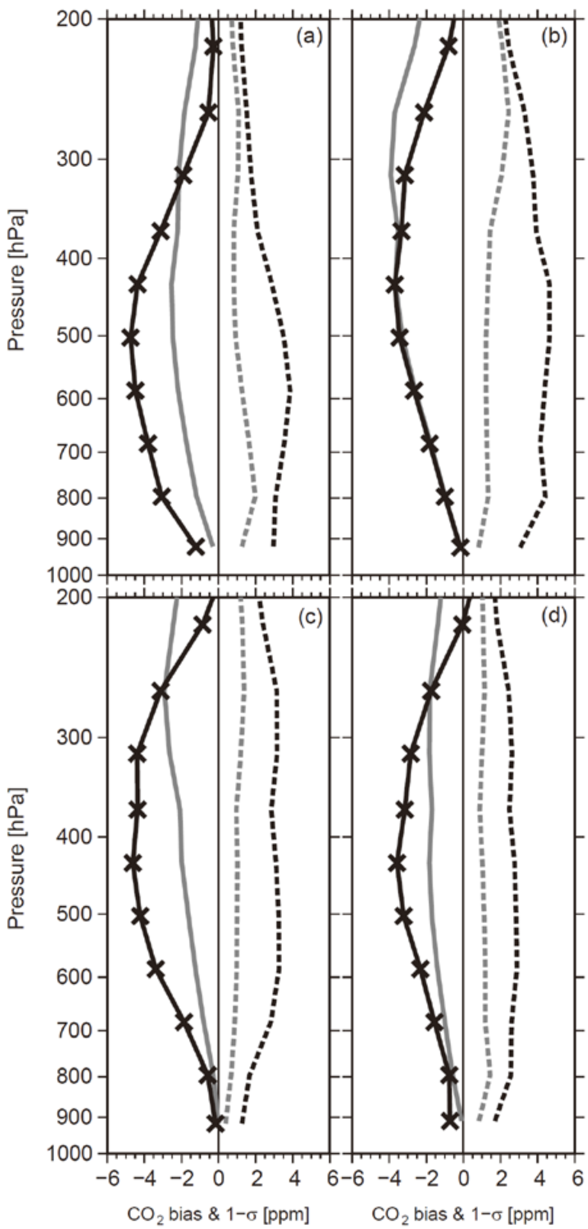


Figure 4. Bias profiles of GOSAT/TASNO-FTS TIR CO_2 data against CME_AK CO_2 data over Narita airport (Japan) using coincident pairs with 24-hour (gray) and 72-hour (black) time difference criteria: (a) winter (JF) 2010 and (b) summer (JJA) 2010.



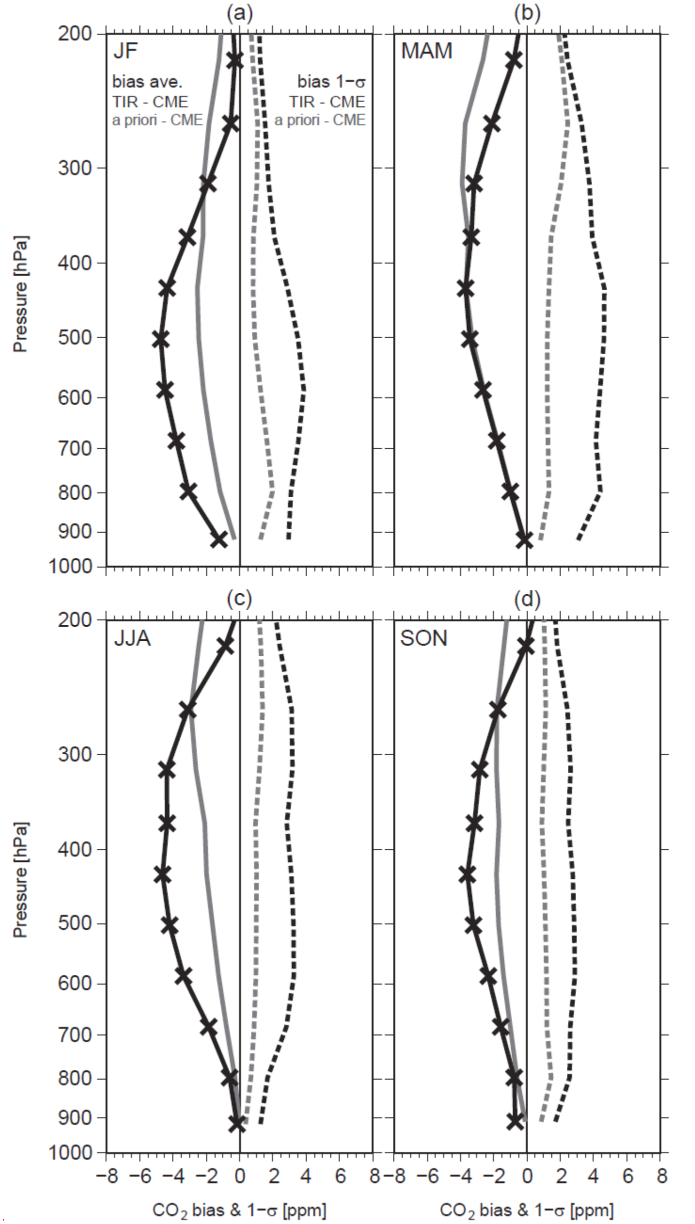
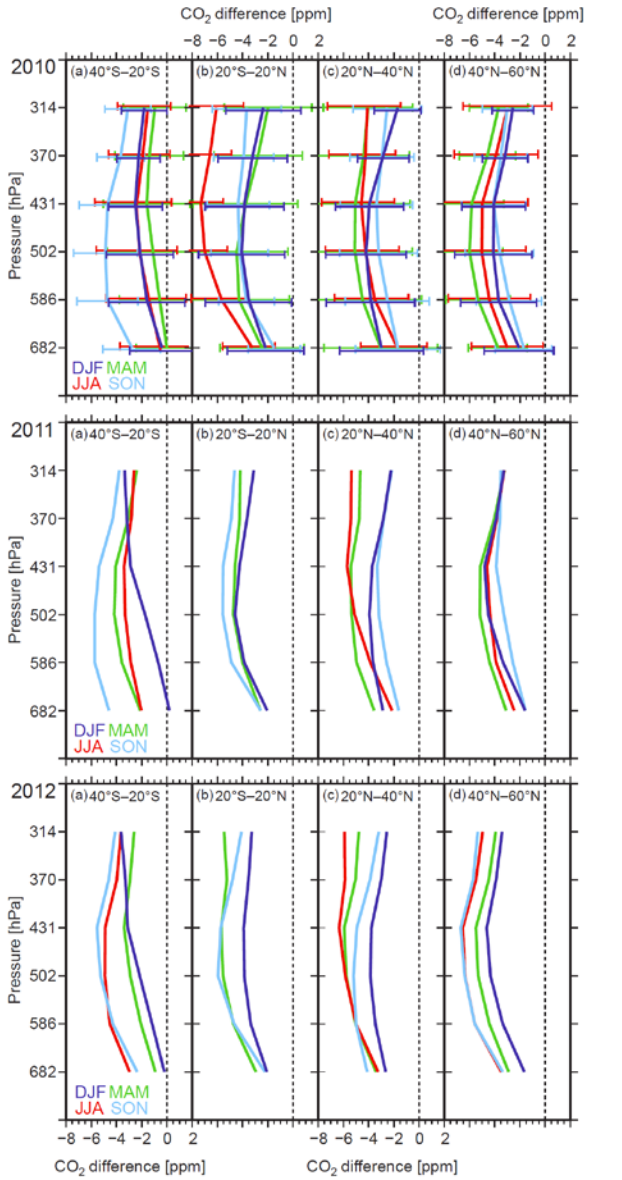
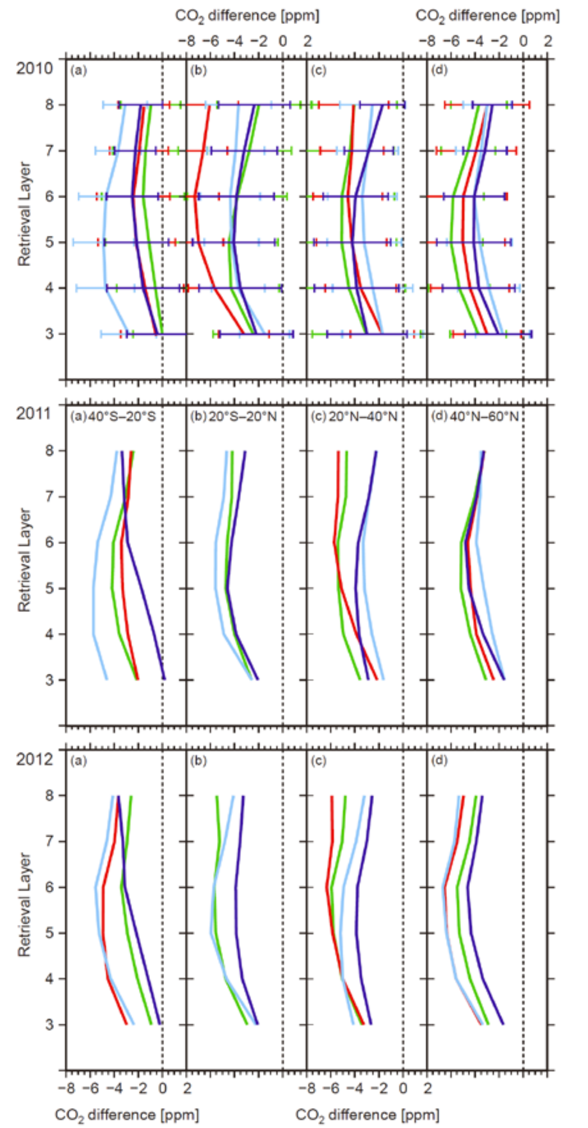


Figure 5. Bias profiles of GOSAT/TANSO-FTS TIR CO_2 data and a priori CO_2 data against CME_AK CO_2 data over Narita airport and the 1-σ standard deviations for each retrieval layer and season in 2010. The CME_AK CO_2 data are CME CO_2 data to which TIR CO_2 averaging kernel functions are applied. SolidThick black and gray lines indicate the biases of TIR and a priori CO_2 data, respectively, and dotted black and gray lines show their 1-σ standard deviations. Cross symbols indicate the center pressure level of each retrieval layer: (a) JF, (b) MAM, (c) JJA, and (d) SON.


CO$_2$ difference [ppm]
CO$_2$ difference [ppm]
2010
(a) 40°S–20°S
(b) 20°S–20°N
(c) 20°N–40°N
(d) 40°N–60°N
Pressure [hPa]
DJF MAM
JJA SON
2011
2012
CO$_2$ difference [ppm]
CO$_2$ difference [ppm]


CO$_2$ difference [ppm]
CO$_2$ difference [ppm]
2010
(a)
(b)
(c)
(d)
Retrieval Layer
2011
(a) 40°S–20°S
(b) 20°S–20°N
(c) 20°N–40°N
(d) 40°N–60°N
2012
CO$_2$ difference [ppm]
CO$_2$ difference [ppm]

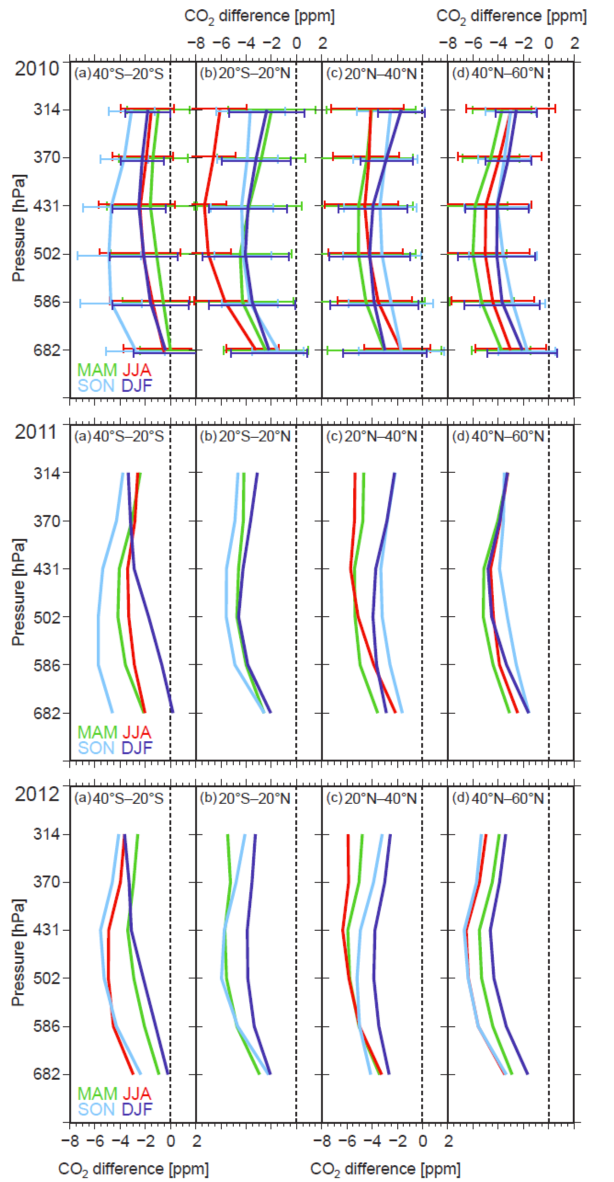
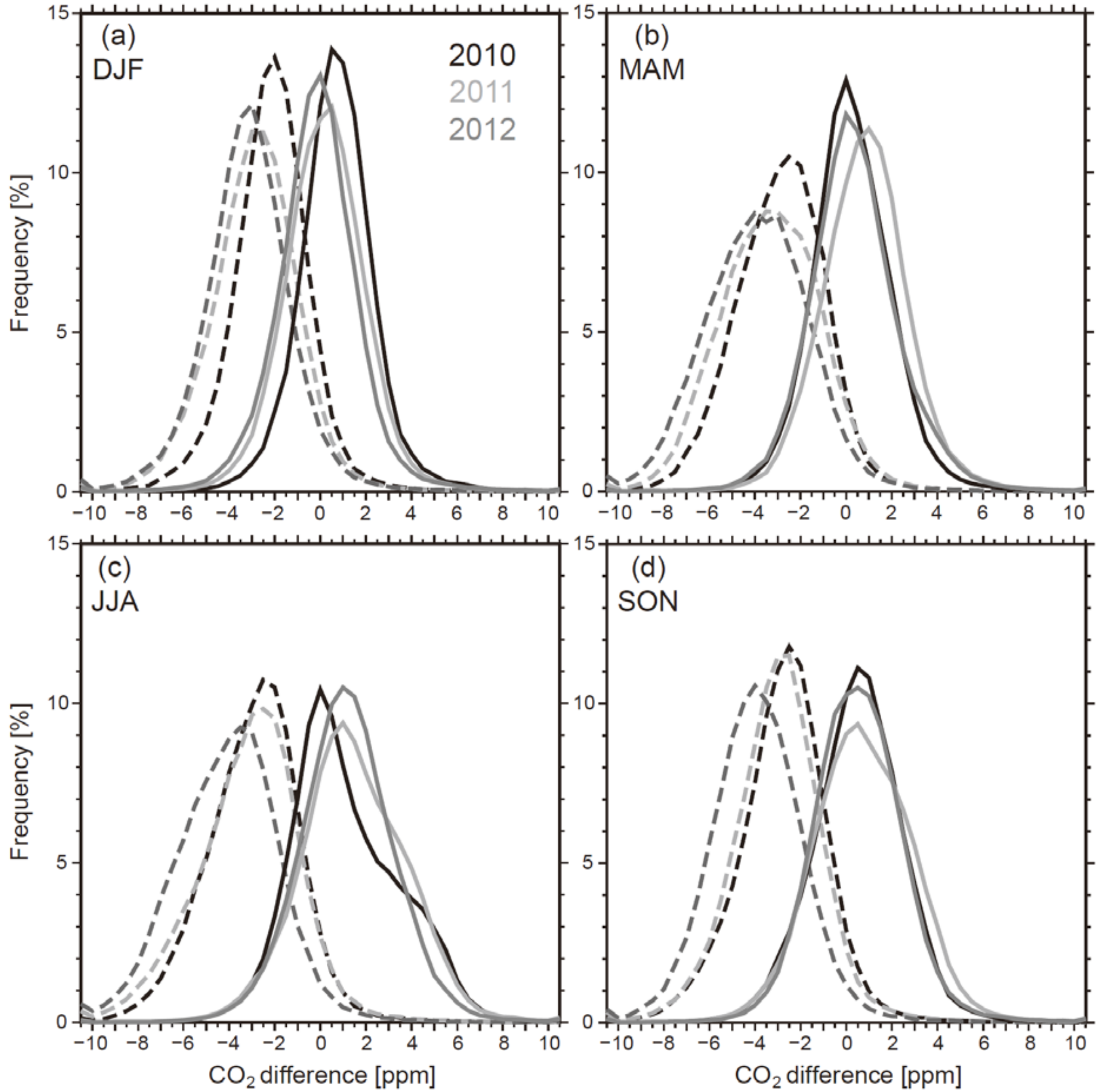
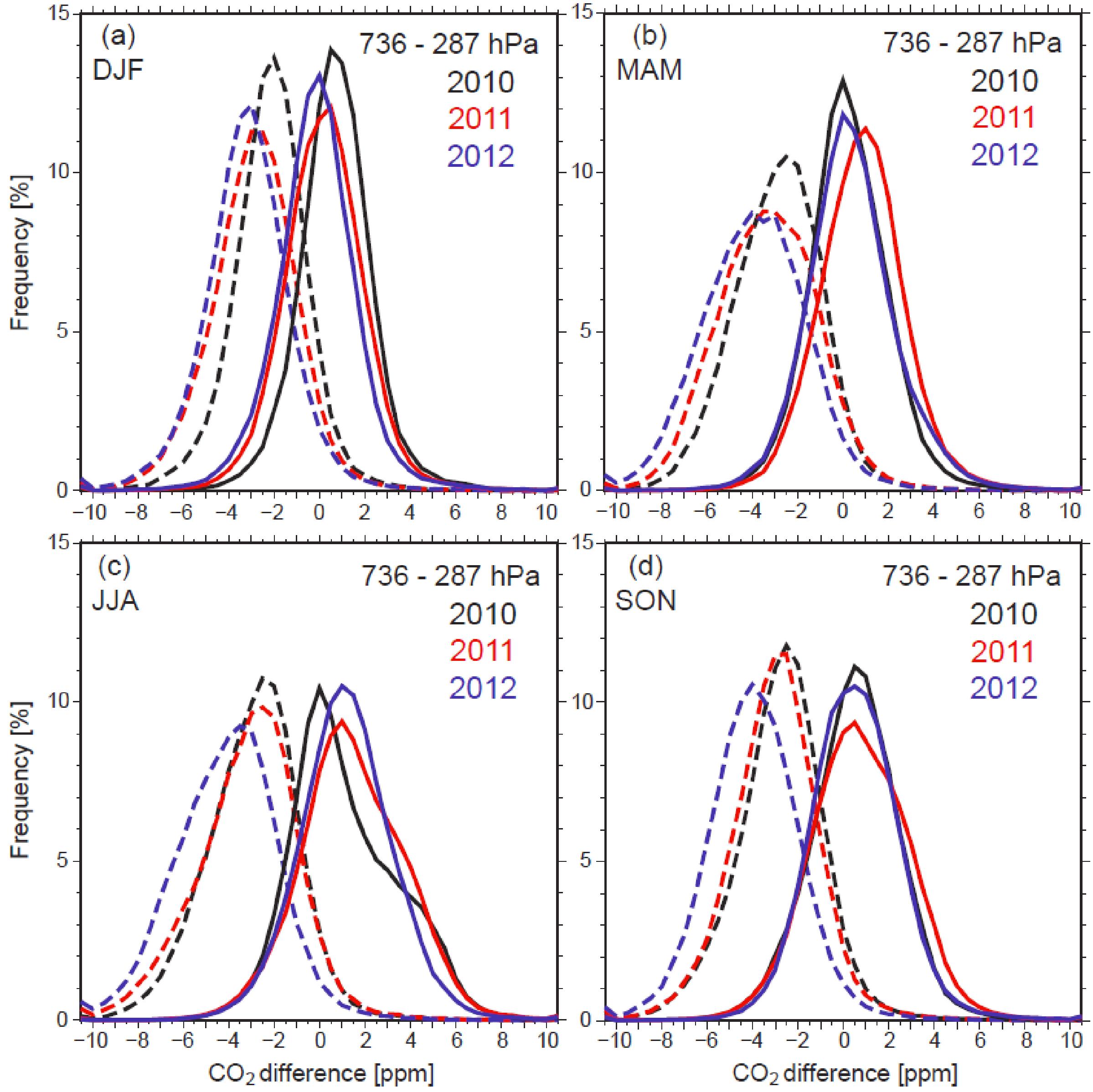


Figure 6. Average differences in CO_2 concentrations between GOSAT/TANSO-FTS TIR and CME_AK CO_2 data (TIR minus CME_AK) from 736 to 287 hPa (in retrieval layers 3 to 8 (736–287 hPa) for each latitude band and season, 2010–2012. The 1-σ standard deviations of the averages are indicated by horizontal bars for comparison of 2010 as a reference, which are slightly shifted up and down for visibility.. We divided the data into four latitude bands: (a) 40°S–20°S, (b) 20°S–20°N, (c) 20°N–40°N, and (d) 40°N–60°N. Green, red, light blue, and blue lines represent the results in northern spring (MAM), northern summer (JJA), northern fall (SON), and northern winter (DJF), respectively.



(a)
DJF
2010
2011
2012
(b)
MAM
(c)
JJA
(d)
SON
Frequency [%]
CO2 difference [ppm]


(a)
DJF
736 - 287 hPa
2010
2011
2012
(b)
MAM
736 - 287 hPa
2010
2011
2012
(c)
JJA
736 - 287 hPa
2010
2011
2012
(d)
SON
736 - 287 hPa
2010
2011
2012
Frequency [%]
CO2 difference [ppm]

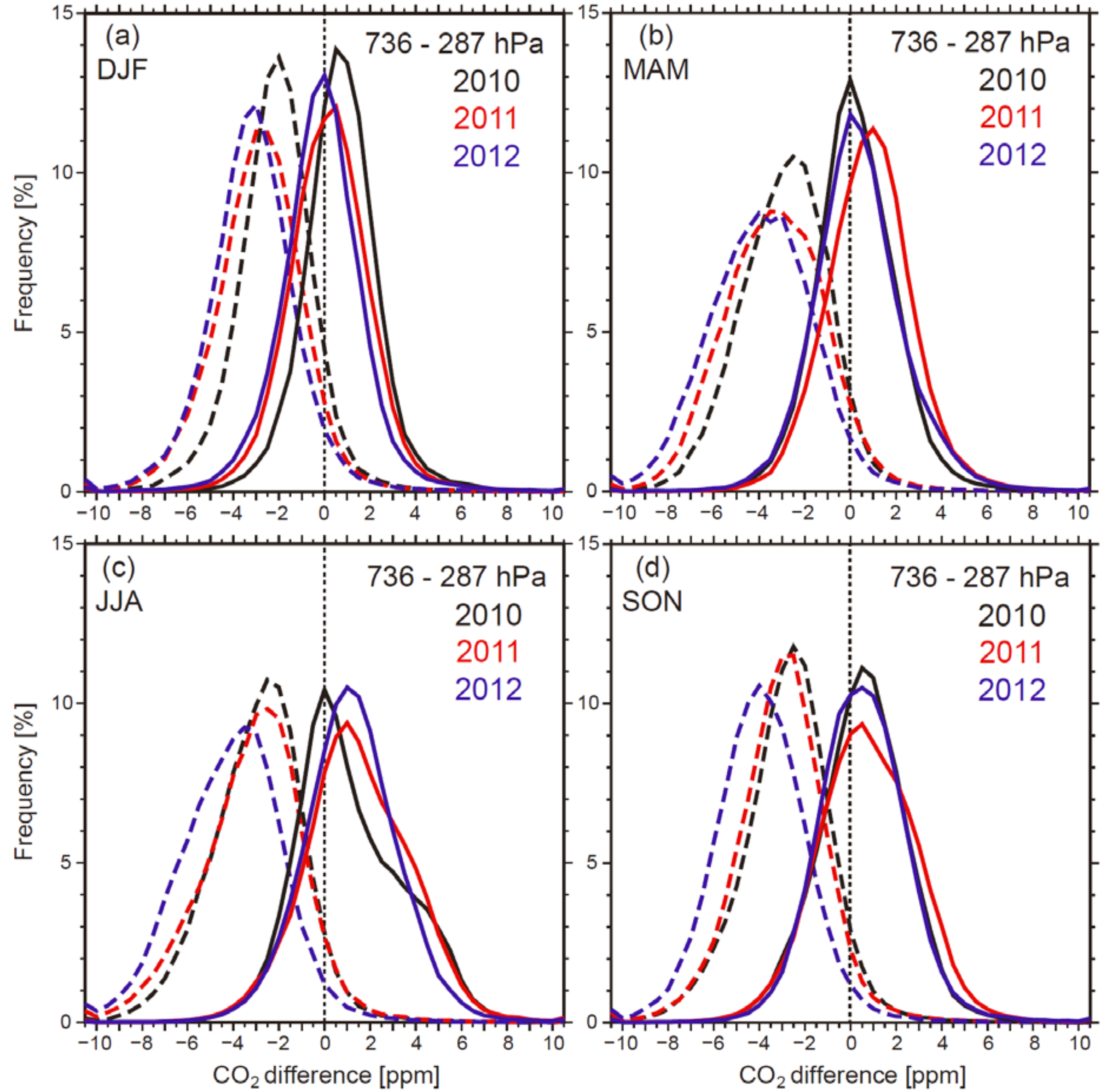
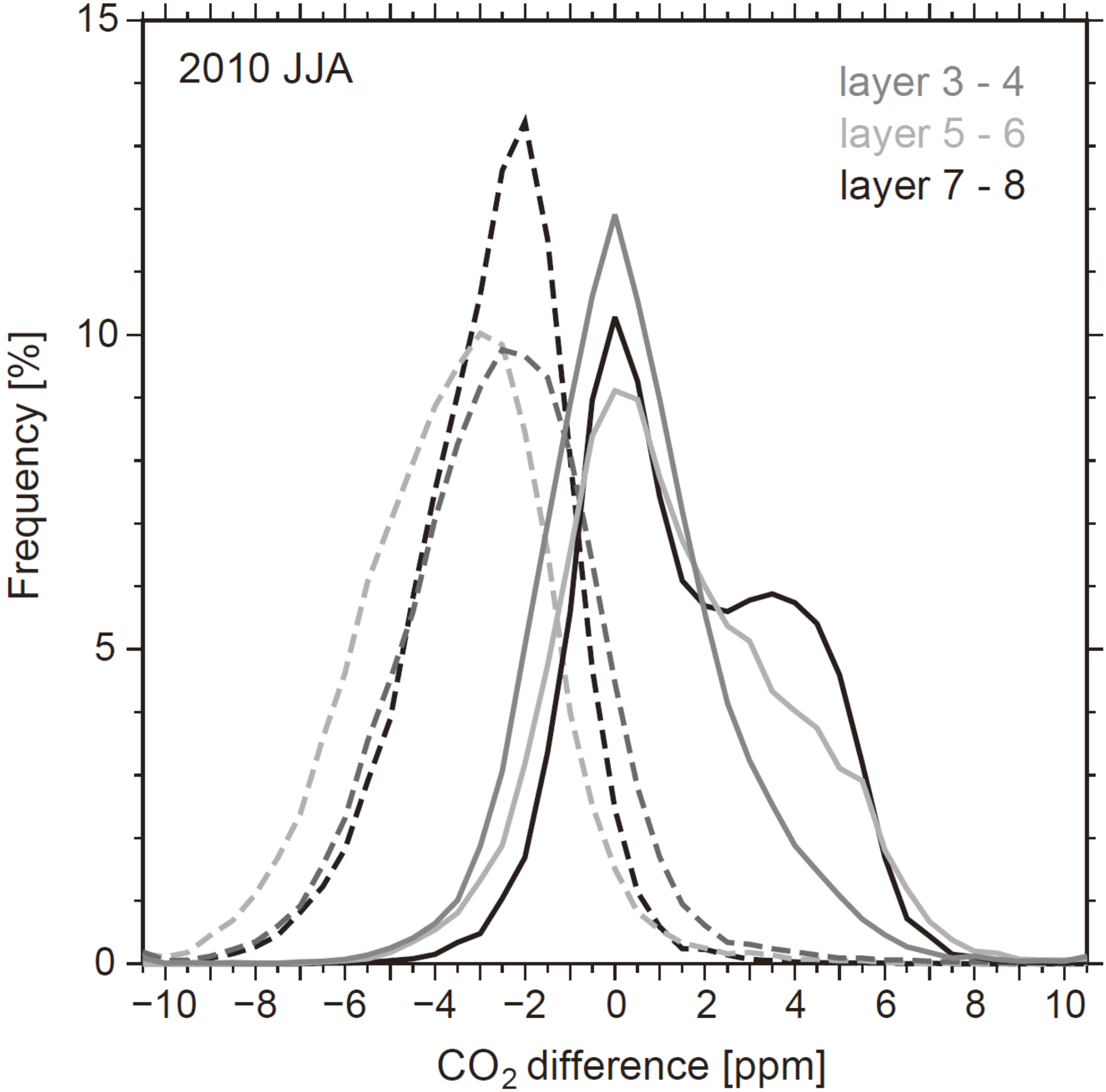
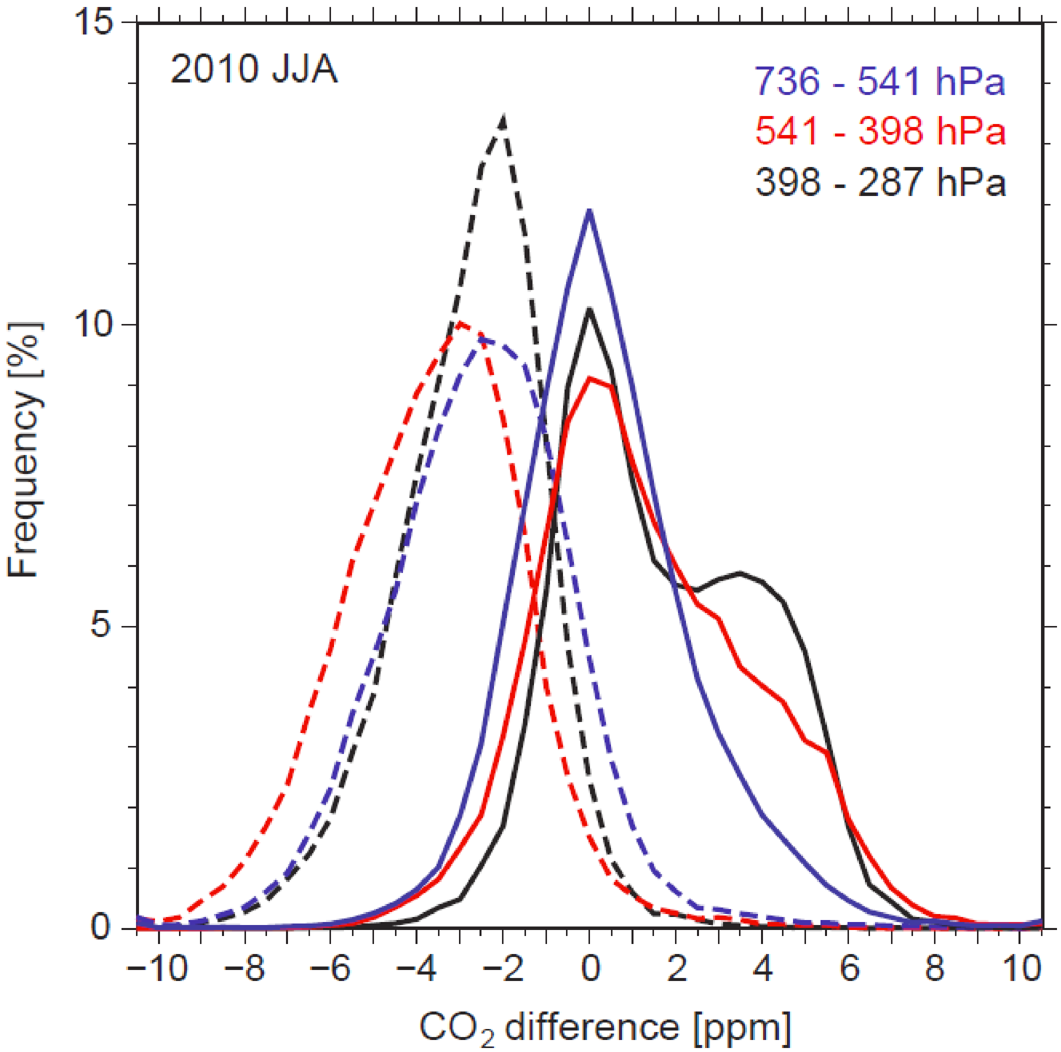


Figure 7. Frequency distributions of biases of monthly averaged GOSAT/TANSO-FTS TIR CO_2 data against monthly averaged NICAM-TM CO_2 data evaluated for each of retrieval layers from 736 to 287 hPa for each 2.5° grid in the latitude range of 40°S–60°N. Monthly averaged TIR CO_2 averaging kernel functions were applied to NICAM-TM CO_2 data in each grid. Thick and dashedDashed and solid lines indicate the biases of the original TIR CO_2 data (no bias correction) and bias-corrected TIR CO_2 data, respectively. Black, redlight gray, and bluedark gray lines show results from 2010, 2011, and 2012, respectively.


2010 JJA
layer 3 - 4
layer 5 - 6
layer 7 - 8
Frequency [%]
15
10
5
0
−10
−8
−6
−4
−2
0
2
4
6
8
10
CO2 difference [ppm]


2010 JJA
736 - 541 hPa
541 - 398 hPa
398 - 287 hPa
Frequency [%]
CO_2 difference [ppm]
15
10
5
0
−10
−8
−6
−4
−2
0
2
4
6
8
10

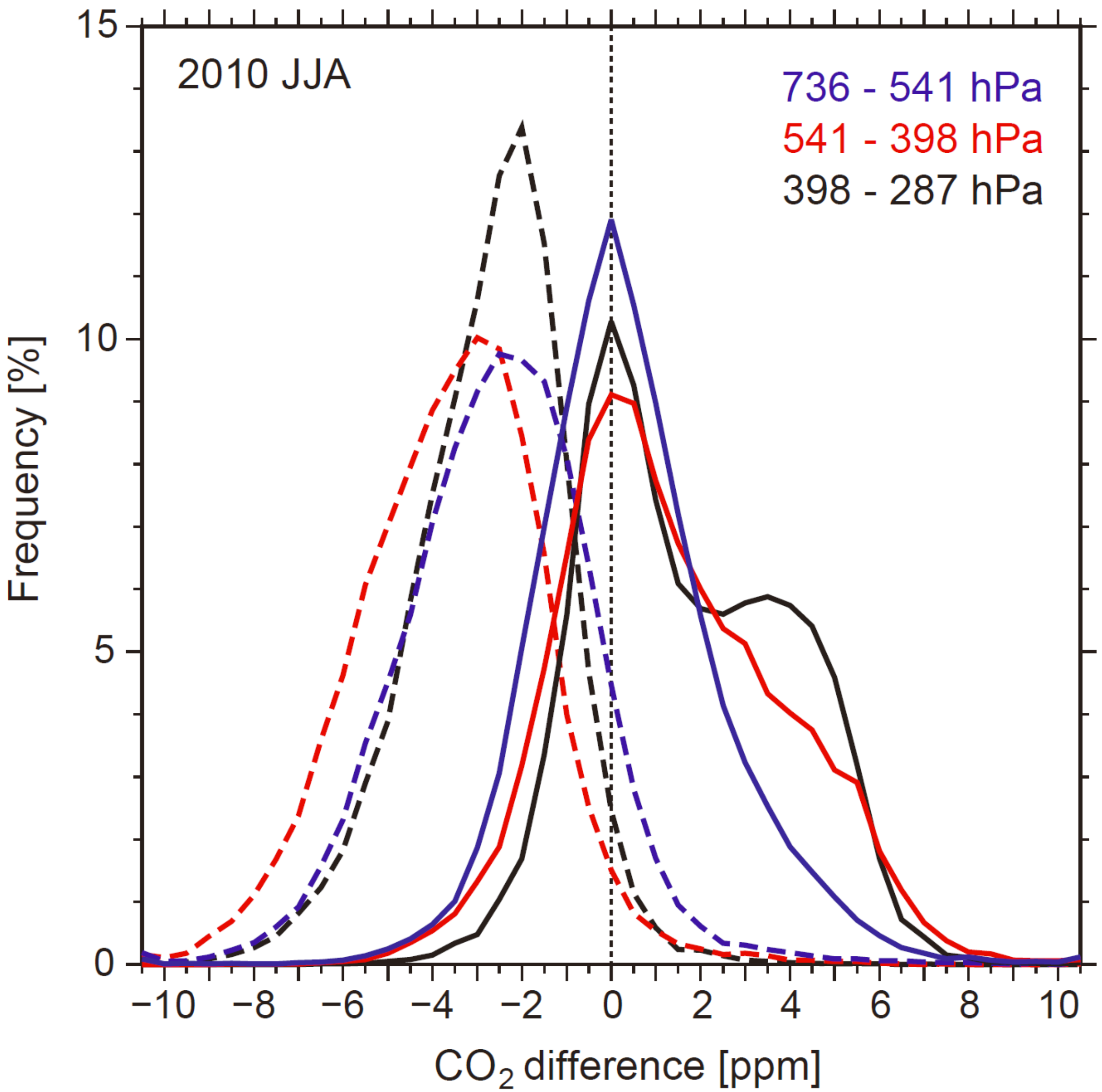
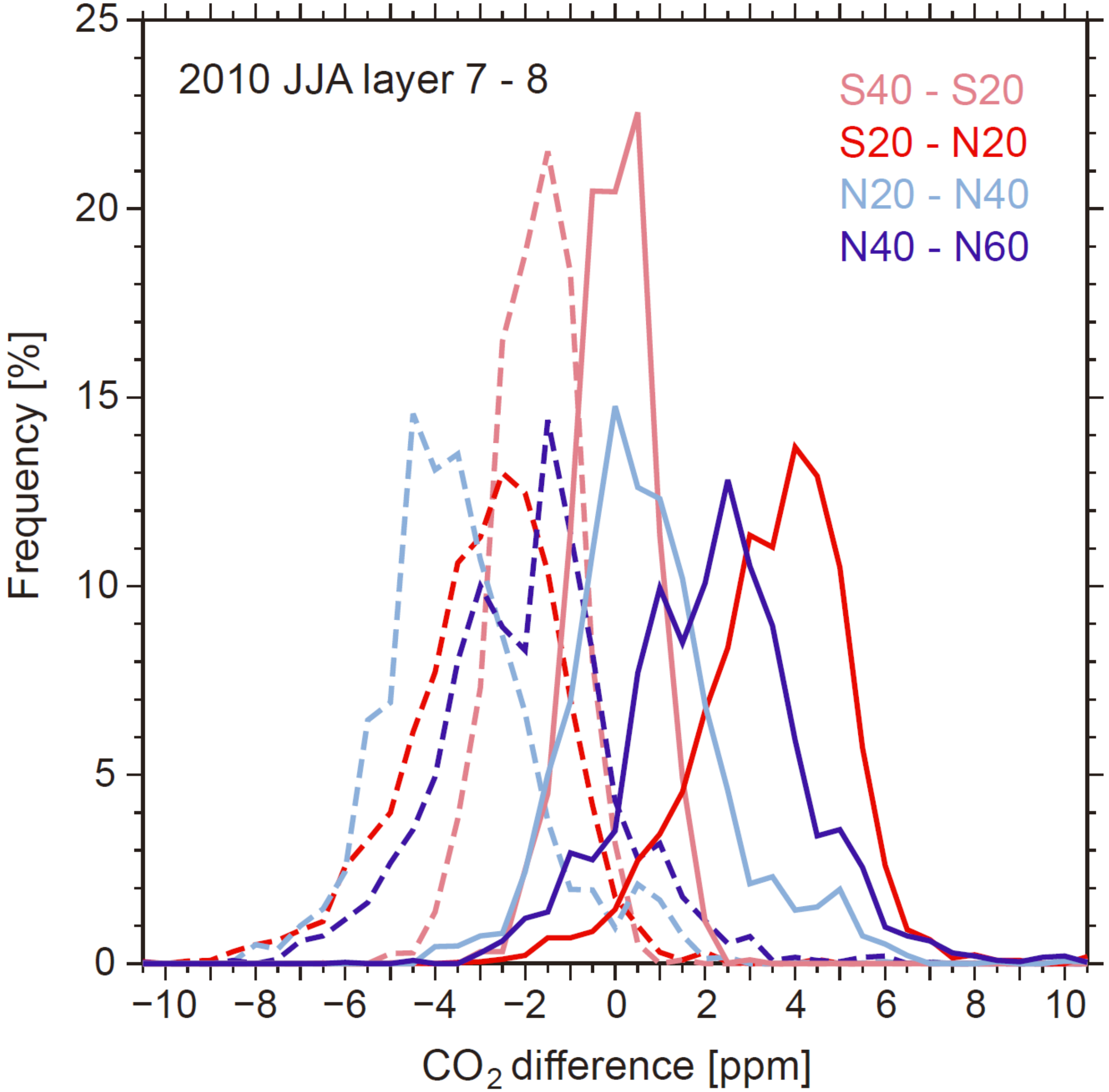
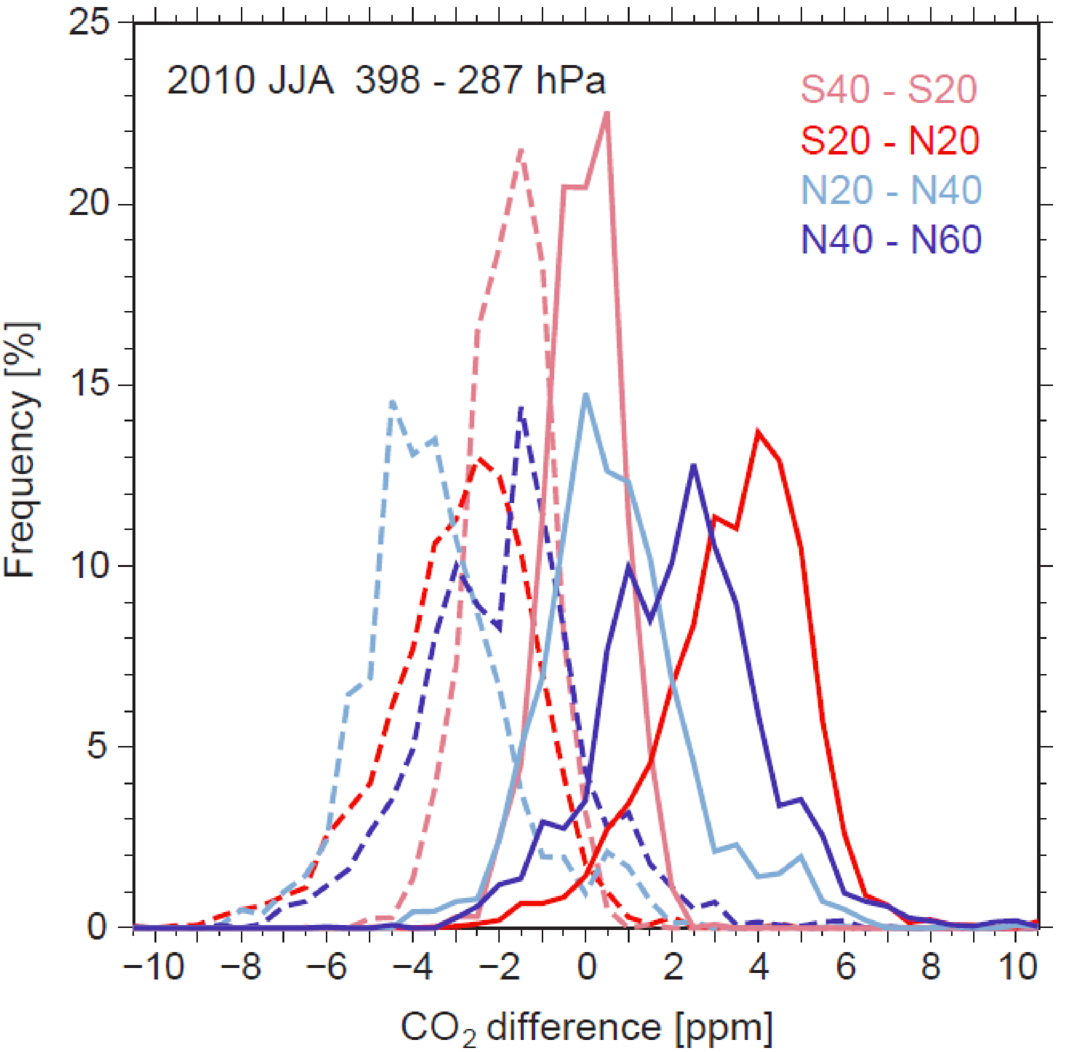


Figure 8. Same as Figure 7, but showing frequency distributions during the JJA season of 2010 on 736–541 hPa (for retrieval layers of 3–4 (736–541 hPa), 5–6 (541–398 hPa (retrieval layers), 5–6), and 7–8 (398–287 hPa) (retrieval layers 7–8). Black, redlight gray, and bluedark gray lines indicate the results on in layers 3987–287 hPa8, 5415–398 hPa6, and 7363–541 hPa4, respectively.


2010 JJA layer 7 - 8
S40 - S20
S20 - N20
N20 - N40
N40 - N60
Frequency [%]
25
20
15
10
5
0
−10
−8
−6
−4
−2
0
2
4
6
8
10
CO2 difference [ppm]



2010 JJA 398 - 287 hPa
S40 - S20
S20 - N20
N20 - N40
N40 - N60
Frequency [%]
CO2 difference [ppm]

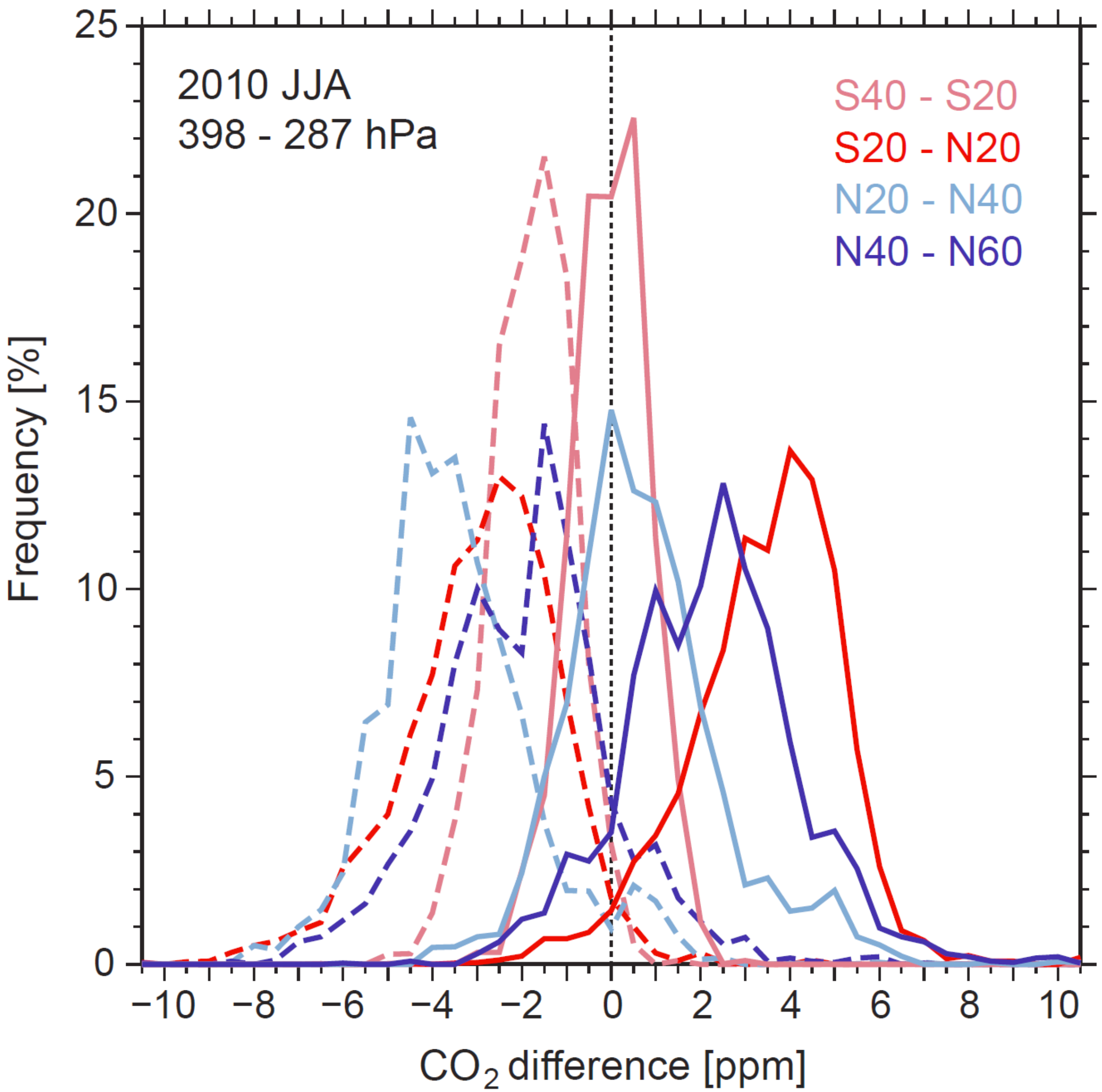
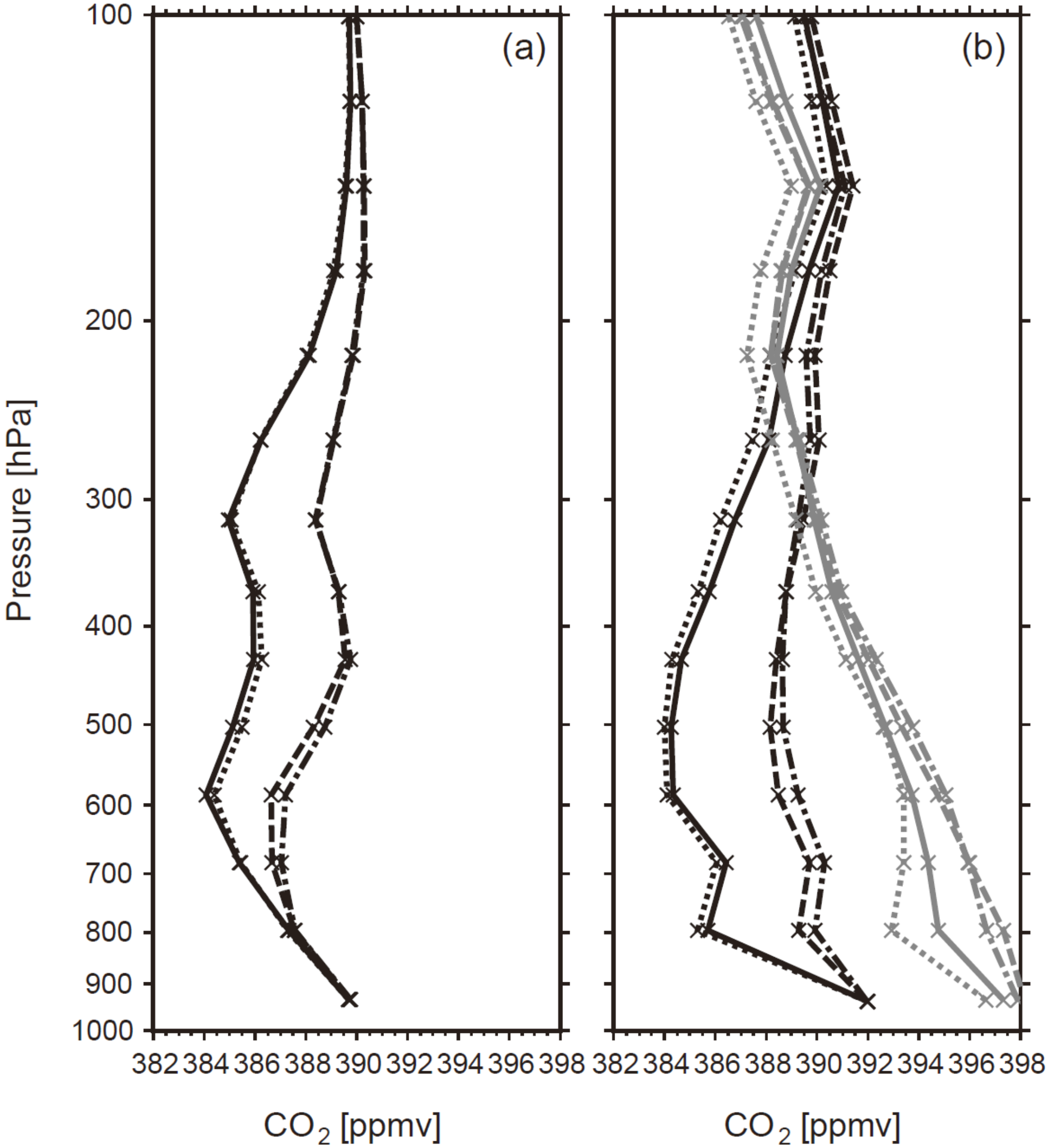


Figure 9. Same as Figure 7, but showing frequency distributions during the JJA season of 2010 on 398−287 hPa (~~for~~ retrieval layers 7–8) for each latitude band. Pink, red, light blue, and blue lines shows the results from 40°S–20°S, 20°S–20°N, 20°N–40°N, and 40°N–60°N, respectively.


(a)
(b)
Pressure [hPa]
100
200
300
400
500
600
700
800
900
1000
382 384 386 388 390 392 394 396 398
CO2 [ppmv]
382 384 386 388 390 392 394 396 398
CO2 [ppmv]

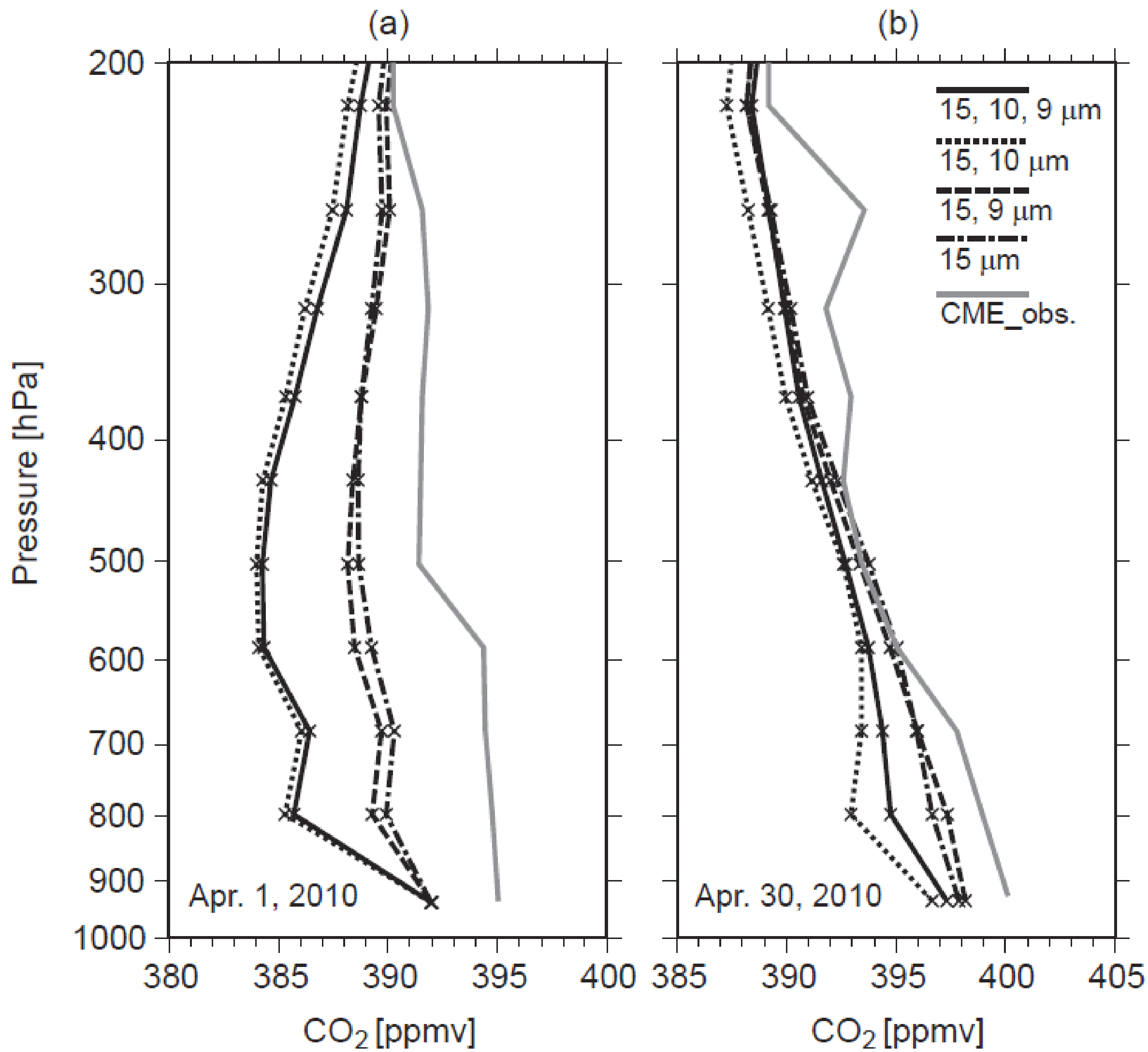


Figure 10. CO_2 profiles over Narita airport retrieved using four different wavelength bands of GOSAT/TANSO-FTS V161 L1B spectra: three bands, 15-μm, 10-μm, and 9-μm (solid~~thick~~ lines); two bands, 15-μm and 10-μm (dotted lines); two bands, 15-μm and 9-μm (dashed lines), and the 15-μm band only (dashed-dotted lines). Nearby CME CO_2 profiles (CME_obs.) are shown by gray lines: (a) a case of April 1, 2010~~A case in low latitudes in summer (July)~~ and ~~and~~ (b) a~~two~~ case~~s~~ of April 30, 2010~~in northern middle latitudes in spring (April)~~.

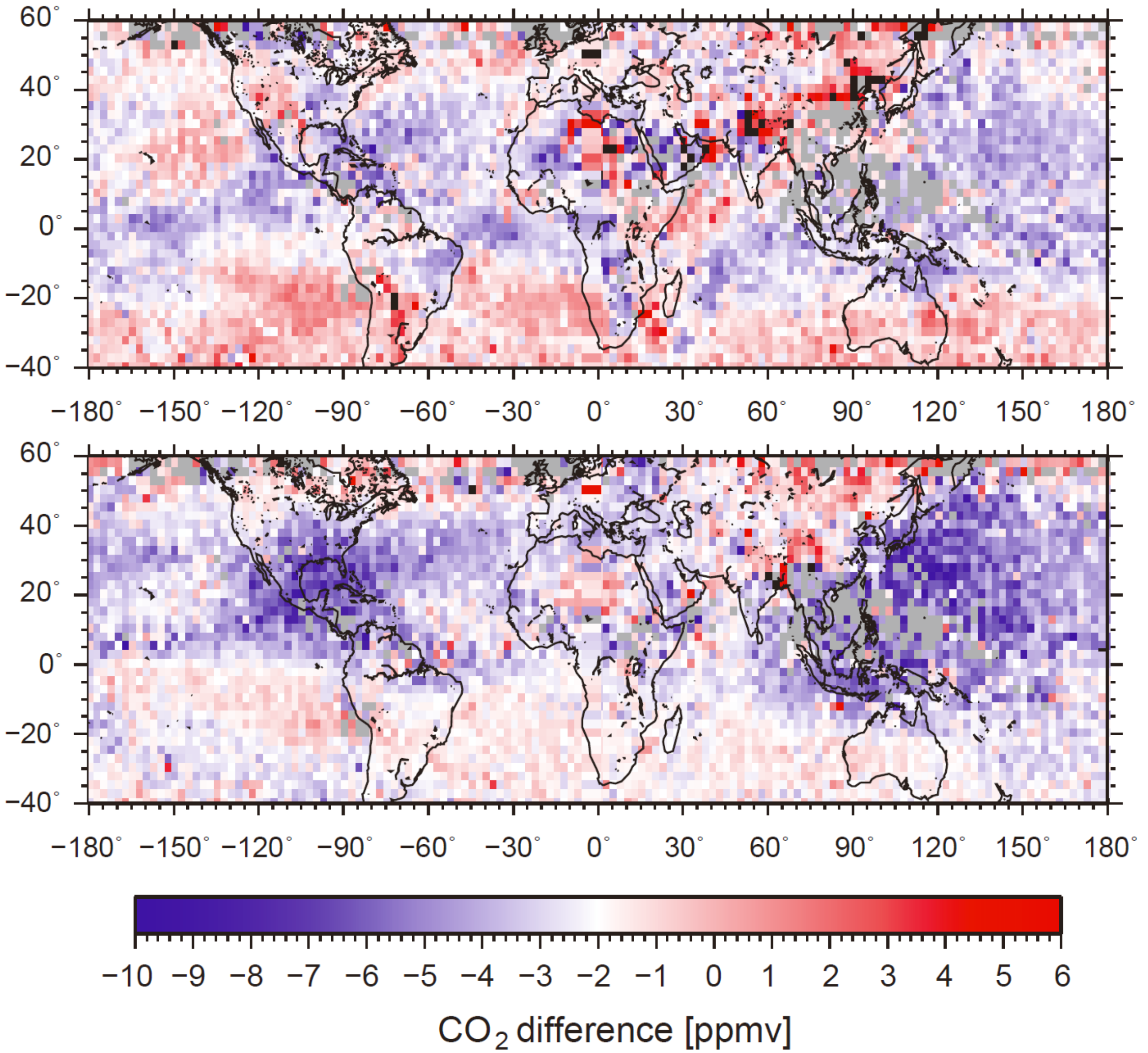


Figure 11. Latitude–longitude cross-sections of differences in monthly averages of GOSAT/TANSO-FTS TIR CO_2 data and NICAM-TM CO_2 data with considering TIR CO_2 averaging kernel functions (TIR minus NICAM-TM) in July 2010. The upper and lower panels show the results on 682 hPa (in retrieval layer 3 (736–631 hPa) and 314 hPa8 (retrieval layer 8341–287 hPa), respectively. There are no GOSAT/TANSO-FTS TIR CO_2 data in gray-shaded areas.