

Interactive comment on “Influence of aerosols and thin cirrus clouds on the GOSAT-observed CO₂: a case study over Tsukuba” by O. Uchino et al.

The authors wish to thank three referees for helpful, thoughtful and insightful comments. Each comment is addressed individually below. The referee comments are in black, and our response are in red.

The main changes to the paper since the APCD version are:

- We replaced simply “revised”, “new”, and “simulated” by “Case 1”, “Case 2” and “Case 3”.
- Figures 1, 5, 6 are combined into Fig.6. The error bars are also added to the Tsukuba TCCON and the retrieved XCO₂ (Case 1 and 2) data.
- In Fig.9 (old Fig.10), the a priori values with the error bars are added to the Tsukuba TCCON and Case 3 XCO₂ data with their error bars.
- We added surface pressures for the version 01.xx and the Case 1 in Fig.7 (old Fig.8).
- We plotted the retrieved AOT at 532 nm for Case 1 and Case 2 with the a priori AOT obtained by lidar in Fig6 (old Fig.7)
- We added the standard deviation of the XCO₂ differences between GOSAT and TCCON in the text.

The following sentences are included in the text.

- The vertical distributions of aerosol and cirrus clouds contribute to a large change in surface pressure, and the aerosol type next with moderate change.
- The small number of comparison is due to severe co-location criterion. The distance from the center of the GOSAT field-of-view to the TCCON station was very small (less than 3 km) since we used the GOSAT data observed over Tsukuba TCCON site. The severe co-location criterion is to exclude the spatial difference of aerosols and cirrus clouds of which variations are comparatively large. The distance of lidar and Tsukuba TCCON site is 513 m.
- The 3-band retrieval approach where the aerosol and cirrus profiles were retrieved gave us the best results and the retrieved XCO₂ data followed the seasonal cycle of ~ 8 ppm observed at Tsukuba TCCON site of which value was consistent to the result by Ohyama et al. (2009).
- In this paper we concentrated our attention on resolving of the large bias of the ver.01.xx results. However, it is important to reduce the regional biases due to distinct regional patterns of aerosols and cirrus clouds for application of

inverse modeling. A 3-band retrieval method where the aerosol and cirrus profiles are retrieved has a possibility of reducing the standard deviations of the biases and the regional biases.

Response to

Anonymous Referee #1

Received and published: 13 December 2011

General Comments

Overall, I found this paper well-written and a useful contribution to the field of satellite remote sensing of CO₂. It postulates a much-needed explanation for the relatively poor performance of the NIES v01.xx operational CO₂ retrieval algorithm, and motivates modifying that algorithm to help resolve some of its issues. Also, this is the first paper that reports using ground-based lidar observations to validate space-based CO₂ observations, and is useful for that reason as well. That said, I have several questions and some suggestions for the authors that will hopefully enhance the paper.

Specific Comments

1. The main upshot of the paper is that retrieving AOD confined to 0-2 km altitude, which is what the operational v01.xx NIES algorithm does, is not sufficient. The authors argue that using more realistic vertical profiles (and types) of aerosol enables better XCO₂ retrievals, but they show little evidence that this is precisely what is going on. The v01.xx algorithm seems to retrieve anomalously high values of aerosol in some cases. I think it would strengthen the paper if the authors talked a little more about what the algorithm specifically retrieves in terms of aerosol optical thickness(es) (AOT), for the different versions of the algorithm (v01.xx, “revised”, and “new”). For instance, please add (and discuss) the retrieved AOT values in the v01.xx algorithm, and how these values change (presumably they decrease) for the “revised” and “new” versions of the algorithm. In the case where aerosol and cirrus are retrieved separately, it would be nice to see how much of each the algorithm is retrieving.

AOT of v01.xx is retrieved at 1600 nm, but AOT in Case 1 and Case 2 is retrieved at 532 nm, so it is not simple to compare them. Instead, we plotted the retrieved AOT at 532 nm for Case 1 and Case 2 with the a priori AOT obtained by lidar in Fig.6. There is no large difference of AOT for Case 1 and Case 2. In spite of longer wavelength, AOT of v01.xx is larger than that in Case 1 and Case 2.

When aerosols and cirrus clouds were observed simultaneously, their retrieved optical thicknesses at 532 nm were summarized in the next table. The values of the parentheses are the

retrieved errors.

		Lidar	Case 1	Case 2
2009/09/11	Aerosol	0.2010	0.2400 (0.0610)	0.1701 (0.0465)
	Cirrus	0.0121	0.0759 (0.0142)	0.0827 (0.0121)
2010/02/14	Aerosol	0.1653	0.1359 (0.0384)	0.1203 (0.0342)
	Cirrus	0.0437	0.0988 (0.0167)	0.0990 (0.0151)

Discussing physical mechanisms would be even better, because we as the reader are left with the impression that this is just retrieval “black magic”; things get better, but we really don’t know why. For instance, for the "revised" algorithm with improved aerosol treatment, does the improvement come mostly from improving the aerosol vertical distribution rather than the aerosol type, or vice versa, or are both equally important?

The vertical distributions of aerosol and cirrus clouds contribute to a large change in surface pressure, and the aerosol type next with moderate change.

Also, do the spectral residuals improve by either of the two algorithm changes, so the changes allow the inversion model to fit the observed spectra better? If so, by how much and in which spectral bands?

If we take into account of the aerosol vertical distribution, the spectral residual (chi-squared) improved in Band 1. There is no large difference of the spectral residuals in Band 1 and Band 2 between Case 1 and Case 2.

2. The metric for a good improvement is stated in the paper as “the differences between GOSAT XCO₂ data and TCCON become much less.” This seems too simplistic and does not identify well-defined metrics other than the overall mean bias amongst the 9 soundings considered. I would recommend stating both the mean and standard deviation of the XCO₂ differences between GOSAT and TCCON. This will allow the reader to see what helps in terms of the overall bias, and what helps to reduce the scatter in the retrievals. Based on Figures 1, 4, and 5, it appears that the new solar model only helps with the bias, but not the scatter, whereas the improved aerosol treatment helps with both the bias and scatter. Therefore, please add these statistics to the discussions on pages 29888, 29893, and 29894.

As Referee suggested, we added the standard deviation of the XCO₂ differences between GOSAT and TCCON in the text.

3. Figures 1, 5, and 6 seem a bit redundant, and don't allow for direct comparison of the different retrievals at the single sounding level. I suggest combining these into a single figure that shows TCCON, v01.xx, revised, and new all on the same plot. If it looks "too busy", you could still have figure 1 as-is, but remove figures 5 and 6, and add a figure that shows retrieved XCO₂ minus TCCON vs. date, for v01.xx, revised, and new.

We combined Figs. 5 and 6 into Fig.1 and replaced simply "revised", "new", and "simulated" by "Case 1", "Case 2", and "Case 3".

4. The XCO₂ statistics are generally given in percent, even though much of our field thinks in terms of parts-per-million (ppm). Would it be possible to change all the difference statistics to be in units of ppm? I realize this is a personal choice, so it is entirely up to the authors to make this change or not.

We changed all the difference statistics in terms of parts-per-million (ppm).

5. It would be useful to see how the retrieved surface pressure changes due to each of the two retrieval modifications, "revised" and "new". Figure 8 currently shows the retrieved surface pressure for "new" only. Could the authors add the Ver 01.XX and the "revised" surface pressures to this figure? Then we could see how much of the improvement in XCO₂ comes from improvement in the retrieved surface pressure.

We added surface pressures for the version 01.XX and the "revised (Case 1)" in Fig.8 (Fig.7 in the revised version).

6. Could the authors briefly explain their colocation (distance) requirements? As far as I can tell, they've used special-target observations so the distance from the center of the GOSAT field-of-view to the TCCON station is very small (less than 2 km), and this causes there to be only 9 soundings for comparison. This would not be obvious to most readers. It directly leads to the "low-number statistics" that this work partially suffers from.

In P29888L24, we inserted following sentences:

The small number of comparison is due to severe co-location criterion. The distance from the center of the GOSAT field-of-view to the TCCON station was very small (less than 3 km) since we used the GOSAT data observed over Tsukuba TCCON site. The severe co-location criterion is to exclude the spatial difference of aerosols and cirrus clouds of which variations are comparatively large. The distance of lidar and Tsukuba TCCON site is 513 m.

Technical Comments

- P29886, top paragraph. This paragraph would read better if the present tense were used. E.g, “In this study, we investigate: : :”; “Next, we show: : :”, etc.

We used the present tense as suggested.

- P29887, L1. “chi-square” ! “chi-squared”

Done.

- P29891, L15-17. I suggest you remove the two sentences on the definition of the single scattering albedo; single scattering albedo is a common parameter and should be well-known to the readers.

We removed the two sentences.

- P29894, L1. Please explain what the “low-frequency baseline correction” is.

Interactive comment on Atmos. Chem. Phys. Discuss., 11, 29883, 2011.

The low-frequency baseline correction is to fit the baseline of the solar irradiance spectra to the calibration data of the solar irradiance by a diffuser installed on the TANSO-FTS.

Response to

Anonymous Referee #2

Received and published: 10 January 2012

The manuscript of Uchino et al. presents a study of CO₂ retrievals from GOSAT over a ground-based validation site in Tsukuba and to study the effect of the aerosol and cirrus treatment of the operational GOSAT algorithm on the accuracy of the retrieved CO₂ columns. Specifically, the study uses ground-based CO₂ column, vertical profiles of aerosol/cirrus backscatter from a lidar and AERONET observations to show that the current approach of the operational algorithm results in biases of several ppm. Using the measured aerosol and cirrus profiles together with an update of the used solar spectrum reduced the underestimation of the GOSAT retrieval from 2.29% to 0.62%. Finally, it is concluded that a 3-band retrieval approach where the aerosol and cirrus profiles are retrieved should give the best results.

This manuscript deals with an important question on how to accurately retrieve CO₂ columns from short-wave infrared measurements in the presence of aerosols and cirrus clouds and approach that is used in this study is interesting.

However, the study is based on a very small dataset and it would also have been beneficial to put the lessons learned into a larger context since it is difficult to draw conclusion on the expected overall improvements on the operational GOSAT retrieval from such a small dataset for a single site. My impression is that the presented study is mostly interesting for retrieval experts and the authors might want to consider if AMT might be a more appropriate journal.

The study concludes that one of the main reasons for the large underestimation in the operational GOSAT retrievals is the use of a 2 band retrieval where only AOT is retrieved and not the profile itself or cirrus clouds. There is a wealth of literature from the OCO team on the 3-band retrieval where the aerosol and cirrus profile is retrieved and the authors might want to consider including at least some of them: Crisp et al., (AMTD, 2011), O'Dell et al., (AMTD, 2011), Boesch et al., (Remote Sensing, 2011), Connor et al., (JGR, 2008), Boesch et al., (JGR, 2006), Crisp et al., (Adv. Space Res., 2004), Kuang et al., (GRL, 2002)

Specific comments:

We included the literature of Crisp et al., (AMTD, 2011), O'Dell et al., (AMT, 2012), Boesch et al., (Remote Sensing, 2011), Connor et al., (JGR, 2008), and Kuang et al., (GRL, 2002).

p. 29885 : : : it is necessary to clarify the global distribution: : : - > to accurately quantify the

Done.

p. 29886 : : : by using Toon's solar irradiance database: : : - > include (Toon et al., 1999, personal communication)

Done.

p. 29886 To suppress bias error, : : : - > To reduce biases, : : :

Done.

p. 29888 Do you have any suggestions why the Tsukuba TCCON FTS has an additional bias. To my knowledge, no such additional factor is needed for any of the other TCCON sites.

About 0.3 ppm and 1 ppm is thought to be due to ghost (laser sampling error of FTS) and instrumental line shape (ILS) of Tsukuba TCCON FTS, respectively. This bias was described by Tanaka et al. (2012) and its correction was reasonable (Wunch et al., 2011b).

p. 29888 Are all GOSAT observations completely spatially collocated with the TCCON site ?

The distance from the center of the GOSAT field-of-view to the TCCON station was small (less than 3 km) since we used the GOSAT data observed over Tsukuba TCCON site.

p. 29889 Is the lidar exactly at the same location as the TCCON instrument?

The distance of lidar and Tsukuba TCCON site is 513 m.

p. 29889 : : : lidar ratio (extinction to backscatter ratio) to be 50 sr : : - > which aerosol type is represented by this lidar ratio and would you need to change this according to the type (dust or sulphate)

The lidar ratios of Asian dust and sulfate are about 50 sr (Sakai et al., 2003; Cattrall et al., 2005) and about 30 sr for maritime aerosol (Cattrall et al., 2005). A paper of Cartell et al.(2005) is included in References.

p. 29894 It might be valuable to have a comparison figure between the Toon and Kurucz solar spectrum

The Kurucz's and Toon's solar spectrum and the ratio are plotted with CO₂ absorption lines in Fig.5.

p. 29894 : : : the retrieved aerosol optical thickness was nearly equal to the a priori value. -> the retrieved aerosol optical thickness was similar to the a priori value

Done.

p. 29894 The retrieval of aerosol optical depth and surface pressure will critically depend on the accuracy of the forward model. Please discuss if line-mixing and collision induced-absorption included in the calculation of the O₂ absorption and if effects from fluorescence or the non-linearity in the interferogram (Frankenberg et al., 2011) are included which will have an impact on surface pressure and AOD retrievals.

Apart from modeling of aerosols and solar irradiance database, the forward model of the present analysis is the same as that of Version 01.xx algorithm described in Yoshida et al. (2011). Line mixing and collision-induced absorption are included in the calculation of O₂ A band absorption. Fluorescence is not included in the forward model. Retrievals of surface pressure and aerosols can also be affected by a zero-level offset, which is observed in Band 1 spectra and is thought to be caused by the instrument's

non-linearity (Butz et al. 2011). To address this issue, we made additional calculations in which a zero-level offset was simultaneously retrieved. We found that there is little effect of a zero-level offset for 6 data from 6 January to 23 February since the signal levels were sufficiently low. For 6 data, the retrieved surface pressures are higher (~5 hPa) than the a priori values, and it could be due to the spectroscopic line parameter database in the O₂ A band.

p. 29894 : : : by interpolating in both time and space the Objective Analysis Data of JMA to obtain values for Tsukuba, with the retrieved values. - > what is Objective Analysis Data ?

It is the gridded meteorological data analyzed from the global observational data.

p. 29894 Section 4.5 (Discussion) includes the final retrieval approach and it might be better to call this section something like ‘Improved 3-band retrieval’

We changed Section 4.5 to “Improved 3-band retrieval (Case 3)”.

p. 29895 These results show that vertical profiles of aerosol species and cirrus clouds must be considered in the retrieval algorithm in order to improve the data quality of the global GOSAT SWIR XCO₂ when lidar observations are not available. -> How important is the correct type?

At least, it is necessary to discriminate between fine and coarse aerosols to consider correctly the wavelength dependence of aerosol optical thickness in the forward model.

p. 29895 The simulated and : : : -> do you mean retrieved ?

Yes, it means retrieved. We replaced simply “revised”, “new”, and “simulated” by “Case 1”, “Case 2”, and “Case 3”.

p. 29895 We also found that use of Band 3 increased XCO₂ by about 2 ppm, but we have not yet identified the origin of this difference. -> Could this simply be spectroscopy?

It might be spectroscopy. Both collisional narrowing and speed dependence of collisional broadening and shifting play a significant role near 1600 nm over a pressure range of 330-67 hPa (Long et al., 2011), where we do not taken into account those effects.

p. 29895 The simulated XCO₂ results shown in Fig. 10 are satisfactory -> Clarify what you mean by satisfactory. What is the mean difference (or standard deviation) and what is required for meaningful retrievals

We replaced “satisfactory” to “promising”.

p. 29895 : : , but the aerosol optical thickness thus obtained could be a source of bias in XCO₂ for retrievals at sites other than the Tsukuba TCCON site.

->This is a bit confusing and you might want to reformulate this sentence. Of course you only know the performance for one site and you would need to carry out validation for other sites. Using an improved SPRINTARS might further improve the results.

Interactive comment on Atmos. Chem. Phys. Discuss., 11, 29883, 2011.

This study is only based on the performance for one site and we would need to carry out validation for other sites. Using an improved SPRINTARS might further improve the results.

Response to

Anonymous Referee #3

Received and published: 10 January 2012

1 Overall Recommendation

The article describes a comparison of GOSAT XCO₂ retrievals with co-located ground based TCCON FTS measurements in Tsubaka, Japan. The authors use ground based lidar and sky radiometer data to derive aerosol and cirrus properties. This data and Toon’s solar spectrum are used for three case studies with modified satellite retrievals showing a distinct improvement of agreement with TCCON.

The paper covers an important and interesting scientific topic, is well written and has an overall clear structure and figures. Nevertheless, the paper gives little new insight into geophysical processes of the carbon cycle. Its focus lies more on the improvement of a satellite remote sensing technique. Therefore, one could argue that the paper fits better to the aims and scopes of a journal like Atmospheric Measurement Techniques – which does not reduce its scientific relevance. If the editor finds that the topic is fitting well into ACP, I would recommend publishing the paper after some major and some minor revisions.

2 Major Comments

Regional Biases: The authors motivate the need for retrieval improvements with systematic biases found by Morino et al. 2011 (P29885L2). However, systematic global biases are not really an issue when thinking about the application of inverse modeling. In contrast, regional varying bias patterns of only a few tenth of a ppm have the potential to hamper inverse modeling (e.g. Miller et al. 2007). This should be discussed

within the paper because clouds and aerosols can produce distinct regional patterns (see e.g. L3 statistics of CALIPSO COT and AOT). This means, an improved NIES algorithm which can better handle clouds and aerosols would have the great potential to reduce regional (or temporal) bias patterns rather than a global offset.

We added the next sentences in Section 5.

In this paper we concentrated our attention on resolving of the large bias of the ver.01.xx results shown by Morino et al. (2010). However, it is important to reduce the regional biases due to distinct regional patterns of aerosols and cirrus clouds for application of inverse modeling. A 3-band retrieval method where the aerosol and cirrus profiles are retrieved has a possibility of reducing the standard deviations of the biases and the regional biases.

Case3: From the first paragraph at P29895 I understand that in case3 a new retrieval has been set up which was applied to the same GOSAT data as before. The results of this retrieval are shown in Fig.10. Within the paper the case3 retrieval is referred to as “simulated XCO₂”. If I misunderstood something I would recommend making the paragraph clearer. If I understood the paragraph correctly, I have the following recommendations/questions:

a) “Simulated” is extremely misleading please find a better name e.g. replace “new”, “revised”, and “simulated” simply by “case1”, “case2”, “case3”.

We replaced simply “revised”, “new”, and “simulated” by “Case 1”, “Case 2”, and “Case 3”.

b) The results shown in Fig.10 agree extremely well with the TCCON FTS measurements. I would estimate from Fig.10 that the standard deviation (TCCON-Simulated XCO₂) is about 0.5ppm. From earlier studies (e.g. Boesch et al. 2011) one can estimate that the theoretically optimal retrieval precision due to SNR over land surfaces can amount already 1ppm under typical viewing geometries. As the TCCON data (even if averaged over 30min) also have a small random error, one would expect that the standard deviation of the difference should be even larger. Studies with real GOSAT data (e.g. Butz et al. 2011) found 2.8ppm. This leads me to the hypotheses that the retrieval of case3 is maybe over-constrained by the a priori. For this reason, I would propose to show XCO₂ a priori within Fig.10 and also the error bars of the a priori and the retrieval results. Additionally, it would be very interesting to discuss within the text how large the influence of the a priori is, i.e. by giving the error reduction.

The difference between the Case 3 XCO₂ and the Tsukuba TCCON XCO₂ data was 0.17 ± 1.49 ppm. The standard deviation of 1.49 ppm (1 σ) is larger than about 1 ppm which

is estimated theoretically optimal retrieval precision due to SNR over most land surfaces for SZAs less than 70 degrees (Boesch et al., 2011). As the error bars of the a priori values are ~16 ppm, the retrieved XCO₂ could not be over-constrained by the a priori. In Fig.9, the a priori values and the error bars of all XCO₂ are added.

c) Why are these very promising results not mentioned within the abstract and in the conclusions?

We added the next sentence in both the abstract and the concluding remarks.

The 3-band retrieval approach where the aerosol and cirrus profiles were retrieved gave us the best results.

Fig.1, 5, 6, and 10: a) It would be much easier to see how the individual retrieval modifications improve the results if these figures were merged into only one figure. b) Please provide error bars for the retrieved XCO₂. This information is available either from the optimal estimation output or from earlier validation studies. c) Please show also the used a priori values.

We included Figs. 5 and 6 in Fig.1 except Fig.10 which is a 3-band retrieval approach.

It is very complex when Fig.10 is included in Fig.1. The used a priori values with large error bars are included in Fig.10. The error bars for retrieved XCO₂ are also provided.

3 Minor Comments

Co-location Criterion: The analyzed period spans over six months but the comparison includes only nine GOSAT measurements. I expect that an extremely strict colocation criterion has been used. Please discuss the used co-location and why it is so strict.

The small number of comparison is due to severe co-location criterion. The distance from the center of the GOSAT field-of-view to the TCCON station was very small (less than 3 km) since we used the GOSAT data observed over Tsukuba TCCON site. The severe co-location criterion is to exclude the spatial difference of aerosols and cirrus clouds of which variations are comparatively large.

Spectroscopic Line Parameter Database: Other XCO₂ retrieval teams found systematic biases of the surface pressure and/or XCO₂. In this context they speculate about in-accuracies of the spectral line parameters of the HITRAN database (e.g. Boesch et al. 2006, Reuter et al. 2011). Some tackle this issue with a bias correction in the post processing and others by modifying the HITRAN line parameters.

Fig.6, 8, and 10 show only minor or no biases. a) Which spectroscopic line parameter database is used? b) Are there indications for biases introduced by the spectroscopic line parameter database?

The forward model is the same as that used by Yoshida et al. (2011). We think there is little direct effect of the offset due to the instrument's non-linearity for 6 data from 6 January to 23 February since the radiance reflected from the surface is dark. For 6 data, the retrieved surface pressures are higher (~5 hPa) than the a priori values, and it could be due to the spectroscopic line parameter database.

Representativeness: How representative is a lidar (point) measurement for a GOSAT pixel with 10km in diameter? One could use this argument also to discuss remaining discrepancies in Case 1 and 2.

A lidar point measurement is not always representative for a GOSAT pixel with 10km in diameter when aerosols and thin cirrus clouds vary rapidly in space and time. This is one of the reasons of remaining discrepancies in Case 2. For example, thin cirrus clouds were variable in time on 14 February.

Fig.1: Is there a reason that XCO₂ retrieval results are sometimes shown in green (Fig.1) and sometimes in blue (Fig.5, 6, 10)?

We used the same color.

Fig.2: Too small.

We made Fig.2 larger.

P29885L9: Add something like “if accurate and precise enough”.

We added the phrase of “if accurate and precise enough”.

P29885L21: Morino et al. 2011 did a side by side comparison. They found for Tsukuba a bias of -6.38ppm. Wouldn't it be better to cite this value, because the results of Morino et al. show that the bias can strongly change from station to station?

We used the value of -7.70 (= -6.38 - 1.32) ppm. The bias of -1.32 ppm was described by Tanaka et al. (2012) and its correction was reasonable (Wunch et al., 2011b).

P29885L29: Several other publications could also be cited in this context, showing that many scientists see great potential in an explicit consideration of aerosol and/or cloud properties: E.g. Bril et al., 2007, Connor et al. 2008, Reuter et al., 2010, Boesch et al.,

2011.

We included publications of Connor et al. 2008, Reuter et al., 2010, and Boesch et al., 2011.

P29887L3: Is the SNR criterion really applied as post processing filter? Why not using it as pre-processing filter?

At present, the SNR is used for post-screening. The threshold of 100 for SNR is very conservative because we want to find the best threshold of SNR using the real data analysis. In near future, we move to pre-screening.

P29887L27: 7751-8000cm⁻¹ referrers only to the O2 band.

We added “6180-6260 and 6297-6382 cm⁻¹ (1567-1588 and 1597-1618 nm)” for CO2.

P29888L12: I think 0.8ppm is the 2sigma uncertainty.

We changed “0.8 ppm (~0.2%)” to “0.8 ppm (2σ)”.

P29888L16: Is “demonstrated” the correct word in this context?

We changed “demonstrated” to “added”.

P29888L19: Caption 2.3 should differ from Caption 2. “Comparison” would be sufficient.

We used “Comparison”.

P29888L23: “About half of the: :” This sentence is misleading, as also the “rejected” data is used for the analysis. (?)

We deleted the sentence. The "rejected" data are used for this analysis.

P29888L27: Don't use sometimes % and sometimes ppm for XCO2 differences. I would suggest using always ppm.

We used only the unit of ppm.

P29889L4: Morino et al. 2011 did a side by side comparison. They found for Tsukuba a bias of -6.38ppm. Wouldn't it be better to compare with this value?

We compared with the value of -7.70 (= -6.38-1.32) ppm. The bias of -1.32 ppm was described by Tanaka et al. (2012) and its correction was reasonable.

P29889L4: “: : :adequately rejects outlying: : :” I find this not so obvious when looking into Tab. 2 and sorting from large to small bias I get (0=reject, 1=quality OK):
001011011.

We deleted the sentence.

P29890L7: I would suggest to consistently using Angstrom exponent alpha (as in Tab4) instead of wavelength exponent Alp.

We used Angstrom exponent alpha for aerosol optical thickness and wavelength exponent Alpha for Mie backscattering coefficient.

P29891L1: “: : :indicate that the retrieval : : : is greatly influenced: : :” sounds somehow contradictory. Correlating the lidar optical thickness (Tab.4) with the CO₂ error (Tab2) gives 0.24 which indicates that the relation is not so obvious.

We added “and their optical thickness” after “thin cirrus clouds”.

P29893L7: I assume that Hess’ cirrus model is used to define all microphysical parameters of the cirrus particles which are not available from the lidar measurements (e.g. phase function). Do the results of case1 critically depend on the used cirrus microphysics (i.e. the used cirrus model) or are the result rather stable?

For the models of Cirrus 1, 2 and 3 by Hess et al. (1998), the differences of the retrieved XCO₂, surface pressure, and AOT are 0.3 ppm, 0.5 hPa, and 0.01 respectively, and the above-mentioned result is rather stable. However, it is better to obtain more examples of thin cirrus clouds before reaching a general conclusion.

P29894L19-25: The focus of this discussion lies in the reduction of the overall bias. However, it should be pointed out that the case study retrievals are capable to follow the seasonal cycle better. I would think that this is the main benefit.

In abstract and concluding remarks, we added “the retrieved XCO₂ data followed the seasonal cycle of ~ 8 ppm observed at Tsukuba TCCON site of which value was consistent to the result by Ohyama et al. (2009)”.

Response to M. K. Dubey, Editor

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**Atmospheric
Chemistry
and Physics
Discussions**

**Interactive comment on “Influence of aerosols and thin cirrus clouds
on the GOSAT-observed CO₂: a case study over Tsukuba” by O.
Uchino et al.**

M. K. Dubey (Editor)

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Dear Uchino and co-authors,

Your paper addresses a very timely retrieval issue for the GOSAT and potentially future CO₂ satellite missions. However, the scientific value and methodology needs to be made clear as noted by two reviewers. Kindly address these issues with diligence so the reviewers can appreciate and accept the value of your research and recommend sharing with the community via ACP.

Cheers! Dubey

The authors think the scientific value of this paper as follows:

As pointed by Referee#1, this paper is the first paper that reports using ground-based lidar observations to validate space-based CO₂ observations. A 3-band retrieved XCO₂ data followed the seasonal cycle of ~ 8 ppm observed at Tsukuba TCCON site, as pointed by Referee #3. As suggested Referee #2, it is important to reduce the regional biases due to distinct regional patterns of aerosols and cirrus clouds for application of inverse modeling. The 3-band retrieval method where the aerosol and cirrus profiles are retrieved has a possibility of reducing the standard deviations of the biases and the regional biases. It will contribute to the understanding of global carbon cycle by the improved GOSAT XCO₂ data.

Influence of aerosols and thin cirrus clouds on the GOSAT-observed CO₂ : a case study over Tsukuba

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Abstract.

Lidar observations of vertical profiles of aerosols and thin cirrus clouds were made at Tsukuba (36.1°N, 140.1°E), Japan, to investigate the influence of aerosols and thin cirrus clouds on the column-averaged dry-air mole fraction of carbon dioxide (XCO₂) retrieved from observation data of the Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer, measured in the Short-Wavelength InfraRed band (TANSO-FTS SWIR), onboard the Greenhouse gases Observing SATellite (GOSAT). The lidar system measured the backscattering ratio, depolarization ratio, and/or the wavelength exponent of atmospheric particles. The lidar observations and ground-based high-resolution FTS measurements at the Tsukuba Total Carbon Column Observing Network (Tsukuba TCCON) site were recorded simultaneously during passages of GOSAT over Tsukuba.

GOSAT SWIR XCO₂ data (version 01.xx) released in August 2010 were compared with the lidar and Tsukuba TCCON data. High-altitude aerosols and thin cirrus clouds had a large impact on the GOSAT SWIR XCO₂ results. By taking into account the observed aerosol/cirrus vertical profiles and using a more adequate solar irradiance database in the GOSAT SWIR retrieval, the difference between the GOSAT SWIR XCO₂ data and the Tsukuba TCCON data was reduced. The 3-band retrieval approach where the aerosol and cirrus profiles were retrieved gave us the best results and the retrieved XCO₂ data followed the seasonal cycle of ~ 8ppm observed at Tsukuba TCCON site.

1 Introduction

The concentration of carbon dioxide (CO₂) increased from about 280 ppm in pre-industrial times (before 1750) to 386.8 ppm in 2009, primarily because of emissions from combustion of fossil fuels and land-use changes (IPCC, 2007; WMO, 2010). Because CO₂ absorbs infrared radiation from the earth's surface, increased CO₂ concentrations lead to a rise in the earth's surface temperature. These changes in temperature influence the biosphere, and the biosphere changes can have a feedback effect on CO₂ concentrations (Cox et al., 2000). To accurately predict future atmospheric CO₂ concentrations and their impacts on climate, it is necessary to accurately quantify the global distribution and variations of CO₂ sources and sinks.

Current CO₂ flux estimates obtained by inverse modeling rely mainly on ground-based observation data. Errors in the estimated regional fluxes in Siberia, Africa, Australia, and South America are particularly large because ground-based monitoring stations are sparse in those regions (WMO, 2010). Spectroscopic remote sensing from space is capable of acquiring data that cover the globe and if those data are accurate and precise enough, it is expected to reduce errors in the CO₂ flux estimation obtained by using inverse modeling (Rayner and O'Brien, 2001; Chevallier et al., 2009; Hungershoefer et al., 2010).

To improve regional CO₂ flux estimates, the Greenhouse gases Observing SATellite (GOSAT) was launched on 23 January 2009 (Kuze et al., 2009) to observe global distributions of CO₂ and methane (CH₄) concentrations from space. Column-averaged dry-air mole fractions of CO₂ and CH₄ (XCO₂ and XCH₄) are retrieved from the Short-Wavelength InfraRed (SWIR) observation data of the Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer (TANSO-FTS) onboard GOSAT (Yoshida et al., 2011). Morino et al. (2011) preliminarily validated the GOSAT SWIR XCO₂ and XCH₄ results by comparing them with reference data obtained by a ground-based high-resolution FTS of the Total Carbon Column Observing Network (TCCON; Wunch et al., 2011a). They found that the GOSAT SWIR XCO₂ and XCH₄ (version 01.xx) values were systematically underestimated by 8.85 ± 4.75 ppm and 20.4 ± 18.9 ppb, respectively. To improve the accuracy of the retrieval results, the causes of these biases (systematic errors) need to be investigated.

Houweling et al. (2005) demonstrated that systematic errors in CO₂ satellite remote sensing data can be caused by aerosols by performing model calculations that showed large sensitivity of the CO₂ column to the vertical aerosol profile. To minimize the errors due to aerosols in SWIR CO₂ measurements from space, Butz et al. (2009) proposed that the amount, vertical distribution, and microphysical properties of aerosol particles

should be parameterized and retrieved simultaneously with the total CO₂ column. Also, some sensitivity studies of aerosols and/or thin cirrus clouds on XCO₂ measured from space have been made (Kuang et al., 2002; Connor et al., 2008; Reuter et al., 2010; Boesch et al., 2011).

The GOSAT SWIR retrieval algorithm in ver. 01.xx assumes that aerosols are uniformly distributed below 2 km of altitude and that no cirrus clouds are present. These assumptions are too simple; therefore, a forward spectrum error due to these assumptions may be one of the major sources of error in GOSAT SWIR XCO₂ and XCH₄ data. In this study, we investigated the impact of vertical aerosol profiles and thin cirrus clouds observed by lidar and sky radiometer on the GOSAT SWIR retrieval results, focusing on the GOSAT SWIR XCO₂ results. First, we compared the GOSAT SWIR XCO₂ data with reference data obtained by a ground-based high-resolution FTS at the National Institute for Environmental Studies (NIES) in Tsukuba, which is part of TCCON (hereafter Tsukuba TCCON FTS). Next, we showed that GOSAT SWIR XCO₂ data are greatly influenced by high-altitude aerosols and thin cirrus clouds observed by lidar. Finally, we demonstrated that by taking into account the vertical aerosol profiles and thin cirrus clouds observed by lidar and sky radiometer, and by using Toon’s solar irradiance database (Toon et al., 1999; personal communication) instead of Kurucz’s database, the difference between the GOSAT SWIR XCO₂ data and the Tsukuba TCCON data becomes much less.

2 Comparison of GOSAT SWIR and Tsukuba TCCON XCO₂ data

2.1 GOSAT SWIR XCO₂

We used GOSAT SWIR XCO₂ ver. 01.xx products. The ver. 01.xx retrieval algorithm uses TANSO-FTS Band 1 (12,900–13,200 cm⁻¹) and Band 2 (5800–6400 cm⁻¹) to simultaneously derive XCO₂ and XCH₄. To reduce biases, auxiliary parameters such as surface pressure and aerosol optical thickness (AOT) are retrieved together with XCO₂ and XCH₄. The GOSAT SWIR ver. 01.xx algorithm focuses on those data obtained under cloud-free conditions, and cloud-contaminated data detected by the TANSO Cloud and Aerosol Imager (TANSO-CAI) onboard GOSAT and TANSO-FTS Band 3 (4800–5200 cm⁻¹) data are excluded from the retrieval analysis. After the retrieval calculations, the quality of the retrieved state is checked from the viewpoints of the convergence (number of iterations, chi-squared, and mean square of the residual spectra for each retrieval sub-band), available information (degrees of freedom for signals and the signal-to-noise

ratio, SNR), and the range of the retrieved AOT values. Details are described by Yoshida et al. (2011).

2.2 Tsukuba TCCON FTS

Solar absorption spectra are measured with a Bruker IFS 120 HR FTS at NIES (36.0513°N, 140.1215°E, 31 m above sea level) in Tsukuba, Japan. Direct solar light is introduced into the FTS with a solar tracker and five gold-coated flat mirrors. The solar tracker is mounted inside a dome on the roof of the building where the FTS is housed. Measurements with the high-resolution FTS are performed according to the TCCON data protocol. A CaF₂ beam splitter and an InGaAs detector are used for the 5500–10,500 cm⁻¹ spectral region. A spectral resolution of 0.02 cm⁻¹ (defined as 0.9 / maximum optical path difference), an aperture size of 0.5 mm, and a scanner velocity of 10 kHz are used as standard parameters for the TCCON measurements. The pressure in the FTS is kept at ~0.03 Torr by an oil-free scroll vacuum pump. The forward and backward scanned interferograms are separately integrated over a period of about 70 s. A weather station also observes meteorological data, recording surface pressure, surface temperature, relative humidity, wind direction and speed, rainfall, and solar radiation intensity at the same site. Table 1 lists the characteristics of the Tsukuba TCCON FTS. Each measured spectrum was obtained by Fourier transform of the interferogram.

Spectra measured with the Tsukuba TCCON FTS were analyzed by using the GFIT nonlinear least-squares spectral fitting algorithm, which is used for retrievals across all TCCON stations (Wunch et al., 2011a).

TCCON XCO₂ is defined as the ratio of the CO₂ column amount to the dry-air column amount. To calculate the dry-air column amount, the GFIT algorithm uses the measured O₂ column amount divided by the known dry-air mole fraction of O₂ (0.2095). The O₂ and CO₂ columns are measured simultaneously using the 7751–8000 cm⁻¹ (1250–1290 nm) and 6180–6260 and 6297–6382 cm⁻¹ (1567–1588 and 1597–1618 nm) spectral bands, respectively. XCO₂ is then obtained as follows:

$$\text{XCO}_2 = 0.2095 \times (\text{CO}_2 \text{ column} / \text{O}_2 \text{ column}) \quad (1)$$

By using the CO₂ to O₂ ratio, systematic and correlated errors present in both retrieved columns are minimized.

The precision of the FTS measurement of XCO₂ is better than 0.2% under clear sky conditions (Washenfelder et al., 2006; Ohyama et al., 2009; Messerschmidt et al., 2010;

Wunch et al., 2011). All TCCON XCO₂ data are corrected for airmass-dependent artifacts (Wunch et al., 2011a). Aircraft profiles obtained over many of these sites are used to empirically scale the TCCON data according to the WMO standard reference scale. The scaling factor of TCCON XCO₂ is 1.011. The uncertainty of TCCON XCO₂ associated with the FTS measurement after scaling by 1.011 has been estimated to be 0.8 ppm (2 σ) by comparing TCCON retrievals with many different aircraft-measured profiles (Wunch et al., 2010).

In 2010, Tsukuba TCCON FTS data were calibrated against data from three aircraft flights and tower measurements of CO₂ concentrations, and an additional bias of -1.32 ± 0.46 ppm (1 σ) was added after airmass-dependent artifact correction and 1.011 scaling (Tanaka et al., 2012). This bias correction was reasonable (Wunch et al., 2011b). Here we use these bias-corrected Tsukuba TCCON XCO₂ data. About 0.3 ppm and 1 ppm is thought to be due to ghost (laser sampling error of FTS) and instrumental line shape (ILS) of Tsukuba TCCON FTS, respectively.

2.3 Comparison

We compared GOSAT SWIR XCO₂ data obtained over Tsukuba on 9 days between September 2009 and March 2010 with Tsukuba TCCON data, using the mean values measured at Tsukuba within 30 min of the GOSAT overpass time (around 12:54 LT) (Fig. 1; Table 2). The small number of comparison is due to severe co-location criterion. The distance from the center of the GOSAT field-of-view to the TCCON station was very small (less than 3 km) since we used the GOSAT data observed over Tsukuba TCCON site. The distance of lidar and Tsukuba TCCON site is 513 m. The severe co-location criterion is to exclude the spatial difference of aerosols and cirrus clouds of which variations are comparatively large.

The GOSAT SWIR XCO₂ data obtained on 14 February 2010 did not converge within the pre-determined maximum iteration number of 20, so we used the XCO₂ value obtained at the 20th iteration. The average difference between GOSAT SWIR XCO₂ and Tsukuba TCCON XCO₂ was -10.99 ± 3.83 ppm, based on all data summarized in Table 2. This is larger than the value of -7.70 ± 2.75 ppm at Tsukuba for an extended comparison and excluding data not meeting quality control criteria (Morino et al., 2011). Next we investigated these results by comparing them with lidar data obtained simultaneously with the GOSAT and Tsukuba TCCON FTS data.

3 Lidar observations of aerosols and thin cirrus clouds over Tsukuba and the influence

of high-altitude particles on GOSAT SWIR XCO₂

A compact lidar, based on a Nd:YAG laser, was developed to observe vertical distributions of thin cirrus clouds and aerosols and evaluate the influence of these particles on GOSAT SWIR XCO₂ data. Two laser wavelengths of 1064 nm (λ_1) and 532 nm (λ_2) are transmitted into the atmosphere through a beam expander. The backscattered light from the upper atmosphere is collected by a telescope and then divided into λ_1 and λ_2 by a dichroic mirror, and λ_2 is further divided into a parallel (P) and a perpendicular component (S) by a polarizer. λ_1 is detected by an avalanche photodiode (APD) and λ_2 by photomultiplier tubes (PMTs). The output signals are processed by transient recorders with an analog/digital converter (A/D) and a photon counter (PC). Table 3 summarizes the characteristics of the lidar (Uchino et al., 2010).

The backscattering ratio R is defined as

$$R = (BR + BA) / BR \quad (2)$$

where BR and BA are the Rayleigh and Mie backscattering coefficients, respectively. Backscattering ratio profiles are derived by the inversion method (Fernald, 1984). We assumed the lidar ratio (extinction to backscatter ratio) to be 50 sr for aerosols (Sakai et al., 2003; Cattrall et al., 2005) and 20 sr for cirrus clouds (Sakai et al., 2003). To calculate BR, we used the atmospheric molecular density profiles obtained by operational radiosondes at the Tsukuba Aerological Observatory of the Japan Meteorological Agency (JMA) (36.06°N, 140.13°E).

The total depolarization ratio (Dep) is defined as

$$\text{Dep} = S / (P + S) \times 100 (\%) \quad (3)$$

where P and S are the parallel and perpendicular components of the backscattered signals. Dep indicates whether the particles are spherical or non-spherical, with large values indicating non-spherical particles. The wavelength exponent of, Alp , which shows whether the Mie particles are small or large, is defined by

$$BA(\lambda) \propto \lambda^{-Alp} \quad (4)$$

Larger values of Alp indicate smaller particles.

Figure 2 shows vertical profiles of R, Dep, and Alp observed on 14, 20, and 23

February 2010. The lidar observations were made during a period of about 10 min as GOSAT passed over Tsukuba. The vertical resolution used for the analysis was 150 m. On 14 February 2010, there were thin cirrus clouds at altitudes of 6.1–10.9 km and aerosols below 3 km. The partial optical thickness at altitudes of 0.4–30 km, τ (0.4–30 km), was 0.24 at 532 nm (Fig. 2). The optical thickness from the surface to the top of the atmosphere could not be obtained below 0.4 km because the beam overlap between the lidar transmitter and receiver was not perfect. Lidar measurements of stratospheric aerosols above 15 km were observed at night (Uchino et al., 2010). In contrast to 14 February, 20 February 2010 was a comparatively clear day with aerosols in the boundary layer, and τ (0.4–30 km) was estimated to be 0.1. On 23 February, the high-altitude aerosols observed at altitudes of 1–5 km were likely dust particles, because Dep was large, indicating non-spherical particles. τ (0.4–30 km) was 0.16.

The difference between GOSAT SWIR XCO_2 and Tsukuba TCCON XCO_2 values was the largest (19.01 ppm) on 14 February 2010 (Table 2). The difference was small (4.86 ppm) on 20 February, and it was somewhat large (12.00 ppm) on 23 February. The cirrus clouds on 14 February 2010 might have influenced the GOSAT retrieval. There were also thin cirrus clouds around 10.9–11.2 km altitude on 11 September 2009, when the difference was also relatively large (11.42 ppm). Our results indicate that the retrieval of GOSAT SWIR XCO_2 data is greatly influenced by high-altitude aerosols and thin cirrus clouds and their optical thickness.

The current version of the retrieval algorithm (ver. 01.xx) assumes that atmospheric aerosols are uniformly distributed from the ground surface to 2 km altitude. Next we show that GOSAT SWIR XCO_2 data were improved when the vertical distribution of the optical thicknesses of aerosols and the thin cirrus clouds observed by lidar and sky radiometer were taken into account.

4 Improvement of GOSAT SWIR XCO_2 retrieval

4.1 Vertical profiles of aerosol species and cirrus clouds

Vertical profiles and optical properties of aerosols and cirrus clouds used in the retrieval analysis were prepared based on the lidar and sky radiometer measurements. The sky radiometer can measure aerosol optical thickness and single scattering albedo at four wavelengths (400, 500, 675, and 870 nm), and the Angstrom exponent can be estimated from the optical thickness at these four wavelengths (Shiobara et al., 1991; Kobayashi et al., 2006). A large value of the Angstrom exponent indicates small particles. Table 4

summarizes the aerosol optical thickness at 500 nm (τ_{500}), the single scattering albedo at 500 nm (ω_{500}), and the Angstrom exponent (α) at the GOSAT overpass times; the optical thickness at 532 nm (τ_{532}), calculated from the lidar measurement by extrapolating the value of BA at 0.4 km down to the ground surface, is also shown. The optical thickness of cirrus clouds is not included in τ_{532} , and it is approximately the same as τ_{500} . The Angstrom exponent of aerosols over Tsukuba was large except on 14 February, 23 February, and 22 March 2010 (Table 4). In addition, the values of ω_{500} were close to unity, indicating that the aerosol particles were small and non-absorbing (Table 4). The relatively small value of α on 14 February 2010 might reflect contamination by cirrus clouds, because the Dep value of the lidar measurement does not indicate the presence of large, non-spherical aerosol particles. We therefore assumed that, except on 23 February and 22 March 2010, the aerosols over Tsukuba were sulfate because the particles were small and non-absorbing.

On 23 February and 22 March, the vertical Dep profiles indicate the presence of large, non-spherical dust-like particles at 2–4 km altitude. We assumed small, non-absorbing aerosols to be sulfate and large particles to be dust. We calculated the optical properties of sulfate aerosols following Takemura et al. (2002), but using a reduced width in the size distribution as suggested by Schutgens et al. (2010). For the dust aerosol model, we used the mineral-transported component of the model of Hess et al. (1998). Using these aerosol models, we determined the dry-mass fraction of sulfate such that the Angstrom exponent of the sulfate–dust mixture agreed with that derived from the sky radiometer observations.

The vertical profiles of the extinction coefficient and the optical thicknesses of sulfate particles and cirrus clouds on 14 February 2010 are shown in Fig. 3, and those of sulfate and dust particles on 23 February 2010 are shown in Fig. 4. Similarly, we obtained vertical profiles of aerosols and cirrus clouds for the other days by using lidar and sky radiometer data observed at Tsukuba.

4.2 Case 1 XCO₂ retrieved using the vertical profiles of particles observed by lidar and sky radiometer

We retrieved XCO₂ (Case 1 XCO₂) by taking account of the vertical profiles of the two types of aerosols and cirrus clouds determined from lidar and sky radiometer data (Table 5, Case 1). In Case 1, we modified the operational ver. 01.xx algorithm as follows. The uniform aerosol distribution up to 2 km altitude was replaced by the vertical profile derived from lidar measurements, as shown in Figs. 3 and 4. The aerosol optical

thickness was then retrieved by scaling the vertical profile. Then we used Mie theory to derive the aerosol optical properties by assuming a mixture of sulfate and dust; for the operational algorithm we adopted aerosol optical properties estimated by the aerosol transport model SPRINTARS (ver. 3.54) (Takemura et al., 2000). In addition, cirrus clouds were included in the forward model on 11 September 2009 and 14 February 2010, when lidar measurements showed that they were present. The optical thickness of the cirrus clouds was retrieved by scaling the vertical profile observed by lidar. To estimate the optical properties of ice crystals in the cirrus clouds, we adopted the Cirrus 3 model of Hess et al. (1998).

We plotted these retrieved values as the Case 1 XCO₂ against the Tsukuba TCCON values (Fig. 1). The difference between the Case 1 XCO₂ and the Tsukuba TCCON XCO₂ data was $7.40 \text{ ppm} \pm 2.39 \text{ ppm}$; thus, these Case 1 XCO₂ data are closer to the TCCON data than the SWIR ver. 01.xx results shown in Fig. 1. In particular, the data for 11 September 2009 and 14 February 2010, when aerosol optical thickness was large (Fig.6) and cirrus clouds were present, and on 23 February and 22 March 2010, when aerosol optical thickness was large, were greatly improved. Nevertheless, although the negative bias in XCO₂ was reduced to one half that obtained with the operational algorithm, it was not eliminated. For the models of Cirrus 1, 2 and 3 by Hess et al. (1998), the differences of the retrieved XCO₂, surface pressure, and AOT were 0.3 ppm, 0.5 hPa, and 0.01 respectively, and the above-mentioned result was rather stable. However, it is better to obtain more examples of thin cirrus clouds before reaching a general conclusion.

4.3 Solar irradiance database

Although a high-resolution solar irradiance database is needed to simulate a TANSO-FTS measured spectrum, few such solar irradiance databases are available. The GOSAT SWIR retrieval analysis used the high-resolution solar irradiance database (0.004 to 0.01 cm⁻¹) of R. Kurucz (<http://kurucz.harvard.edu/sun/irradiance2008/>). This database was created from spectra measured with a ground-based high-resolution FTS at Kitt Peak National Observatory (Arizona, USA) by removing the absorption structure due to the earth's atmosphere. However, as shown in Fig.5, we noticed a CO₂ absorption structure in the spectral residual between the measured spectrum and the spectrum simulated by the forward spectral model, whereas when we used a solar spectrum database provided by G. C. Toon (personal communication; Toon et al., 1999), we confirmed no CO₂ absorption structure in the spectral residuals. We thus decided to use Toon's solar irradiance database. We also applied the low-frequency baseline

correction in the current ver. 01.xx retrieval to Toon's solar irradiance database. The low-frequency baseline correction is to fit the baseline of the solar irradiance spectra to calibration data of the solar irradiance by a diffuser installed on the TANSO-FTS.

4.4 Case 2

We retrieved XCO₂ (Case 2 XCO₂) data by using Toon's solar irradiance data instead of Kurucz's data and by taking into account the vertical profiles of the two types of aerosols and cirrus clouds determined by lidar and sky radiometer (Table 5, Case 2), and plotted these Case 2 XCO₂ values against the Tsukuba TCCON data (Fig. 1). The difference between the Case 2 XCO₂ and Tsukuba TCCON XCO₂ data was 2.43 ± 2.45 ppm. Thus, the Case 2 XCO₂ data were much closer to the Tsukuba TCCON XCO₂ data than the GOSAT SWIR (Ver. 01.xx) data (Fig. 1). A lidar point measurement is not always representative for a GOSAT pixel with 10km in diameter when aerosols and thin cirrus clouds vary rapidly in space and time. This is one of the reasons of remaining discrepancies in Case 2. For example, thin cirrus clouds were variable in time on 14 February.

We compared the retrieved optical thickness at 532 nm with that of the a priori lidar data (Fig. 6) and found that, in general, the retrieved aerosol optical thickness was similar to the a priori value. There is no large difference of AOT for Case 1 and Case 2. In spite of longer wavelength, AOT of v01.xx is larger than that in Case 1 and Case 2. We also compared the a priori surface pressure, obtained by interpolating in both time and space the Objective Analysis Data (the gridded meteorological data analyzed from the global observational data) of JMA to obtain values for Tsukuba, with the retrieved values (Fig. 7). The difference between the a priori and the Case 2 retrieved surface pressure was small except on 11 October 2009 compared with that for the Case 1. Therefore, it is reasonable to infer that the Case 2 XCO₂ data are reliable. However, the retrieved surface pressures improved largely compared with those of version 01.xx. The vertical distributions of aerosol and cirrus clouds contribute to a large change in surface pressure, and the aerosol type next with moderate change. If we take into account of the aerosol vertical distribution, the spectral residual (chi-squared) improved in Band 1. There is no large difference of the spectral residuals in Band 1 and Band 2 between Case 1 and Case 2.

Apart from modeling of aerosols and solar irradiance database, the forward model of the present analysis is the same as that of version 01.xx algorithm described in Yoshida et al. (2011). Line mixing and collision-induced absorption are included in the calculation of O₂ A band absorption. Fluorescence is not included in the forward model. Retrievals of surface pressure and aerosols can also be affected by a zero-level offset,

which is observed in Band 1 spectra and is thought to be caused by the instrument's non-linearity (Butz et al. 2011). To address this issue, we made additional calculations in which a zero-level offset was simultaneously retrieved. We found that there is little effect of a zero-level offset for 6 data from 6 January to 23 February since the signal levels were sufficiently low. For 6 data, the retrieved surface pressures are higher (~ 5 hPa) than the a priori values, and it could be due to the spectroscopic line parameter database in the O₂ A band.

4.5 Improved 3-band retrieval (Case 3)

In this study, we demonstrated that the negative bias of 10.99 ± 3.83 ppm for all GOSAT SWIR XCO₂ data in Table 2 at the Tsukuba TCCON site could be reduced to 7.40 ± 2.39 ppm by taking into account the vertical profiles of aerosols and cirrus clouds observed by lidar and sky radiometer. The negative bias in XCO₂ was then further reduced to 2.43 ± 2.45 ppm by using Toon's solar irradiance data instead of Kurucz's data.

These results show that vertical profiles of aerosol species and cirrus clouds must be considered in the retrieval algorithm in order to improve the data quality of the global GOSAT SWIR XCO₂ when lidar observations are not available. One of the simplest ways to improve the treatment of aerosols would be to incorporate vertical profiles of aerosols obtained from SPRINTARS in the forward model. Aerosol vertical profiles simulated by SPRINTARS, however, are not sufficient, as shown by comparing the SPRINTARS aerosol profile with that observed by lidar (Fig. 8). Therefore, as the first step, we simultaneously retrieved XCO₂ (Case 3 XCO₂; Table 5, Case 3) and the vertical profile of aerosol optical thickness based on the a priori aerosol optical thickness profile calculated by SPRINTARS. In Case 3, the optical thickness and cloud-top pressure of the cirrus clouds were also retrieved simultaneously. The cloud-bottom pressure was modeled as a linear function of the cloud-top pressure, as suggested by N. Eguchi (personal communication; Eguchi et al., 2007), and the cirrus clouds were assumed to be distributed uniformly in the vertical direction. In addition, Band 3 spectra ($4790\text{--}4910$ cm⁻¹) were also utilized in Case 3 for higher retrieval accuracy of the vertical aerosol profiles.

The Case 3 and Tsukuba TCCON XCO₂ values are shown in Fig. 9. We also plot the a priori XCO₂ values calculated by the National Institute for Environmental Studies Transport Model (NIES TM) and their errors which were assumed to be the 100 times of the original CO₂ variance-covariance matrix (refer to Yoshida et al. (2011)). The

difference between the Case 3 XCO₂ and the Tsukuba TCCON XCO₂ data was 0.17 ± 1.49 ppm. The standard deviation of 1.49 ppm (1 σ) is larger than about 1 ppm which is estimated theoretically optimal retrieval precision due to SNR over most land surfaces for SZAs less than 70 degrees (Boesch et al., 2011). As the errors of the a priori values are ~ 16 ppm, the retrieved XCO₂ could not be over-constrained by the a priori. Although information on the vertical profiles of aerosols and cirrus clouds observed by lidar was not used in retrieving the Case 3 XCO₂, the Case 3 values were considerably closer to the Tsukuba TCCON XCO₂ values than current retrievals by GOSAT SWIR XCO₂ (Fig. 1). We also found that use of Band 3 increased XCO₂ by about 2 ppm, but we have not yet identified the origin of this difference. It might be attributed to be spectroscopy. Both collisional narrowing and speed dependence of collisional broadening and shifting play a significant role near 1600 nm over a pressure range of 330-67 hPa (Long et al., 2011), where we do not taken into account those effects.

Aerosol optical properties derived from SPRINTARS were used in both Case 3 and the current operational algorithm. The Case 3 XCO₂ results shown in Fig. 9 are promising. We know this study is only based on the performance for one site and we would need to carry out validation for other sites. An improved SPRINTARS might further improve the results. Therefore, it would be better to use a new SPRINTARS model in which AERONET observations are assimilated (Schutgens et al., 2010). Furthermore, SPRINTARS is being further improved by assimilation of lidar network and CALIOP data (Shimizu et al., 2004; Winker et al., 2007; Sekiyama et al., 2010).

5 Concluding remarks

Version 01.xx GOSAT SWIR XCO₂ data, released in August 2010, were compared with Tsukuba TCCON data. Comparison of lidar and sky radiometer observations with the GOSAT SWIR XCO₂ data clearly showed that high-altitude aerosols and thin cirrus clouds had a large impact on GOSAT SWIR XCO₂. The current retrieval algorithm (ver. 01.xx) for XCO₂ and XCH₄ from the GOSAT TANSO-FTS SWIR observation data assumes that atmospheric aerosols are uniformly distributed from the ground surface to 2 km altitude. By taking into account the actual vertical distributions of aerosols determined by lidar and sky radiometer over Tsukuba, and by using Toon's solar irradiance database instead of Kurucz's database, the difference between GOSAT SWIR XCO₂ data and the Tsukuba TCCON XCO₂ found in the ver.01.xx results was reduced. The 3-band retrieval approach where the aerosol and cirrus profiles were retrieved gave us the best results and the retrieved XCO₂ data followed the seasonal cycle of ~ 8 ppm

observed at Tsukuba TCCON site of which value was consistent to the result by Ohyama et al. (2009).

In this paper we concentrated our attention on resolving the large bias of the ver.01.xx results shown by Morino et al. (2011). However, it is important to reduce the regional biases due to distinct regional patterns of aerosols and cirrus clouds for application of inverse modeling. The 3-band retrieval method where the aerosol and cirrus profiles are retrieved has a possibility of reducing the standard deviations of the biases and the regional biases. Recently the NASA Atmospheric CO₂ Observations from Space (ACOS) team applied this 3-band retrieval to GOSAT data (O'Dell et al., 2012; Crisp et al., 2012). In the near future, we plan to incorporate the vertical distributions of aerosols at altitudes above 2 km in the GOSAT SWIR retrieval algorithm.

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Table 1. Characteristics of the Tsukuba TCCON FTS.

Instrument type	Bruker IFS 120 HR
Beam splitter	CaF ₂
Aperture size	0.5 mm
Detector	InGaAs (5000-10500 cm ⁻¹), Si diode (9200-14000 cm ⁻¹)
Spectral resolution	0.02 cm ⁻¹
Single-scan observation time	70 s

Table 2. Comparison of GOSAT SWIR XCO₂ (A) with Tsukuba TCCON XCO₂ (B) and the quality control items not satisfactory for data release. Aerosol optical thickness (AOT) was retrieved at the wavelength of 1600 nm. SNR is signal-to-noise ratio.

Date	A(ppm)	B (ppm)	A – B (ppm)	AOT	Quality control
11 Sep 2009	371.02	382.44	-11.42	1.092	AOT > 0.5
11 Oct 2009	376.58	385.62	-9.04	0.429	
6 Jan 2010	376.34	389.68	-13.34	0.233	SNR = 94.5 at band 1
27 Jan 2010	381.31	391.20	-9.89	0.410	
5 Feb 2010	380.33	390.20	-9.87	0.141	
14 Feb 2010	372.42	391.43	-19.01	0.928	not converged AOT = 0.93
20 Feb 2010	386.41	391.27	-4.86	0.176	
23 Feb 2010	379.41	391.41	-12.00	0.453	
22 Mar 2010	380.66	390.10	-9.44	1.011	AOT > 0.5

Table 3. Characteristics of the two-wavelength polarization lidar.

Transmitter			
Laser	Nd:YAG		
Wavelength	532 nm		1064 nm
Pulse energy	150 mJ		150 mJ
Pulse repetition rate		10 Hz	
Beam divergence		0.2 mrad	
Receiver			
Telescope type	Ritchy-Chretien (advanced)		
Telescope diameter		30.5 cm	
Field of view (full angle)		1.0 mrad	
Interference filter (FWHM)	0.28 nm		0.38 nm
Transmission	58%		58%
Polarization measurement	Yes		No
Number of receiving channel	3 (P:2, S:1)		1
Detector	PMT (R3234-01)		APD (Silicon)
Transient recorder	12bit A/D + PC		12bit A/D
Minimum time resolution		1 minute	
Minimum altitude resolution		7.5 m	

Table 4. Optical thickness at 500 nm (τ_{500}), single-scattering albedo at 500 nm (ω_{500}), and Angstrom exponent (α) observed by sky radiometer, and aerosol optical thickness at 532 nm (τ_{532}) determined by lidar at Tsukuba.

Date (yyyy/mm/dd)	Sky radiometer			Lidar
	τ_{500}	ω_{500}	α	τ_{532}
2009/09/11	0.276	0.956	2.102	0.201
2009/10/11	0.087	0.840	2.095	0.098
2010/01/06	0.079	1.0	2.120	0.091
2010/01/27	no data	no data	no data	0.160
2010/02/05	0.093	1.0	2.364	0.146
2010/02/14	0.230	1.0	1.534	0.165
2010/02/20	0.109	0.999	2.130	0.116
2010/02/23	0.279	0.997	1.416	0.181
2010/03/22	0.180	0.999	0.785	0.187

Table 5. Physical parameters currently used for retrieval (Ver. 01.xx) and three case studies showing decreased biases of GOSAT SWIR XCO₂ data.

	Aerosol vertical profile	Aerosol optical characteristics	Cirrus	Solar irradiance database
Ver. 01.xx	0~2 km	SPRINTARS	No	Kurucz
Case 1	lidar	sulfate and dust	Yes	Kurucz
Case 2	lidar	sulfate and dust	Yes	Toon
Case 3	Retrieved (SPRINTARS as a priori data)	SPRINTARS	Yes	Toon

Figure captions

Fig. 1. Comparison of TANSO-FTS SWIR XCO₂ (ver. 01.xx) data with the Tsukuba TCCON, Case 1 and Case 2 XCO₂ results. The Case 1 and Case 2 XCO₂ are retrieved using Kurucz's and Toon's solar irradiance data, respectively. Both cases are taking into account the vertical profiles of two types of aerosols and cirrus clouds determined from lidar and sky radiometer (Table 5). The error bars for the Tsukuba TCCON data and the retrieved XCO₂ are also shown.

Fig. 2. Vertical profiles of the backscattering ratio R , total depolarization ratio Dep , and wavelength exponent Alp , observed by lidar on 14, 20, and 23 February 2010. $\tau_{0.4-30}$ (0.4–30 km) is the partial optical thickness at altitudes of 0.4–30 km at 532 nm.

Fig. 3. Vertical profiles of the optical thicknesses (left panel) and extinction coefficients (right panel) of sulfate and cirrus cloud particles at 532 nm on 14 February 2010. The vertical scale is pressure normalized to surface pressure. The values of 0.5 and 0.1 correspond to altitudes of about 5.5 and 16 km, respectively.

Fig. 4. Vertical profiles of optical thicknesses (left panel) and extinction coefficients (right panel) of sulfate and dust particles at 532 nm on 23 February 2010.

Fig. 5. The Kurucz's and Toon's solar spectrum and the ratio are plotted with CO₂ absorption lines.

Fig. 6. Comparison of retrieved optical thickness at 532 nm (Case 2) with a priori values estimated from lidar measurements. The error bars of the retrieved values are also shown.

Fig. 7. Comparison of retrieved surface pressure (Case 2) with a priori pressure. The error bars of the retrieved values are also shown.

Fig. 8. Vertical profiles of aerosol optical thickness measured by lidar and simulated by SPRINTARS at 532 nm on 23 February 2010.

Fig. 9. Comparison of Case 3 XCO₂ data, obtained by retrieving the aerosol profile based on the a priori vertical profile and fixed aerosol optical characteristics given by the SPRINTARS model, with the Tsukuba TCCON XCO₂ data (Table 5, Case 3). The used a priori values and their error bars are also shown.

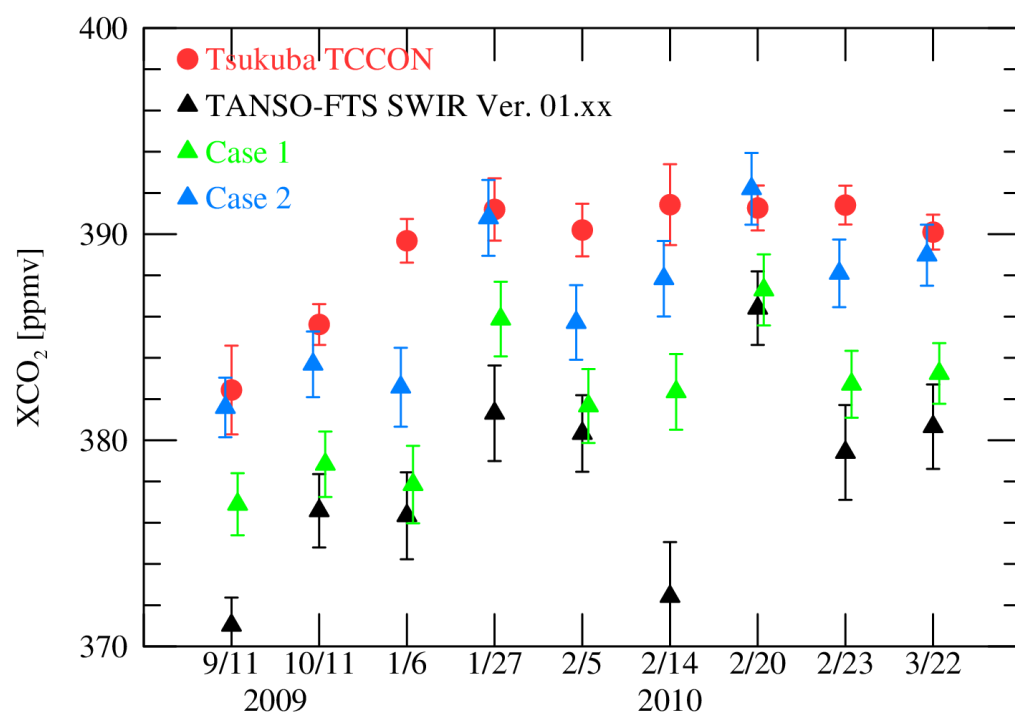


Fig. 1.

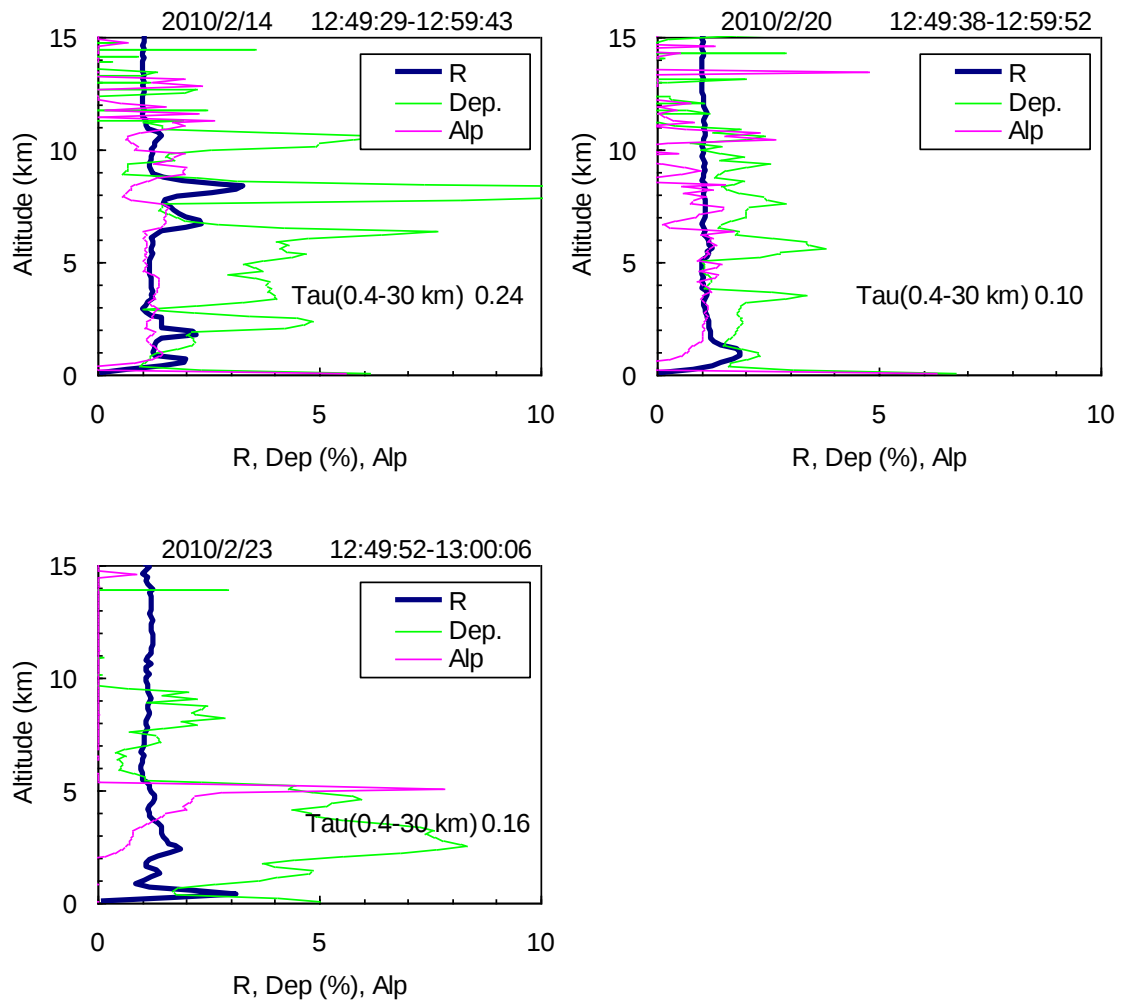


Fig. 2.

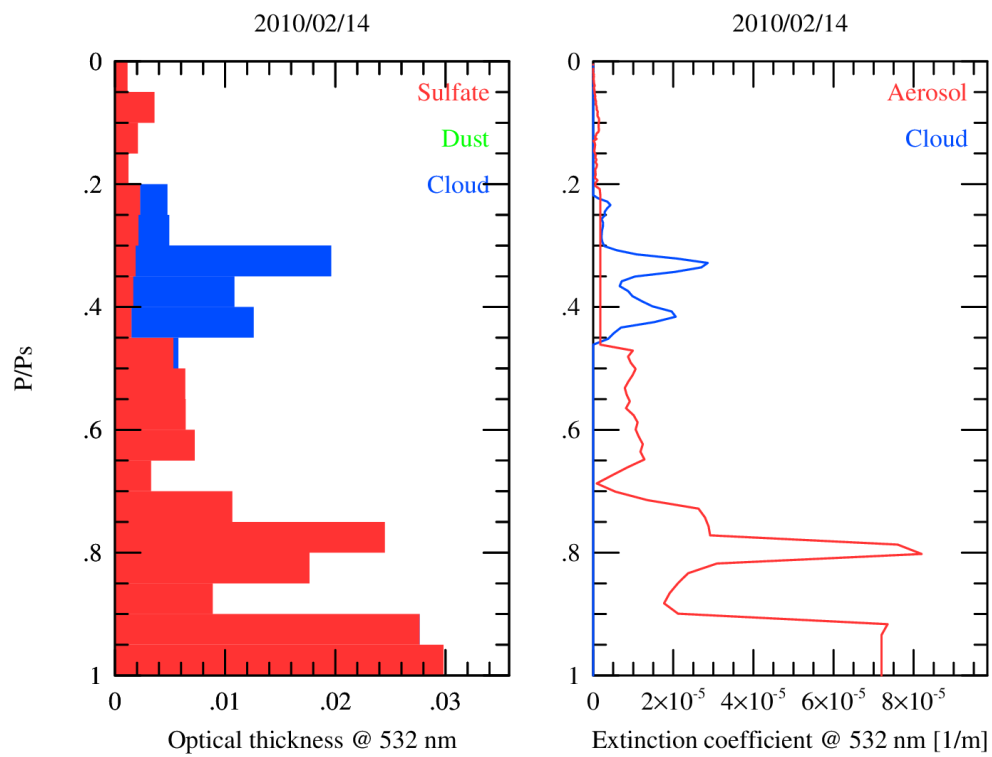


Fig. 3.

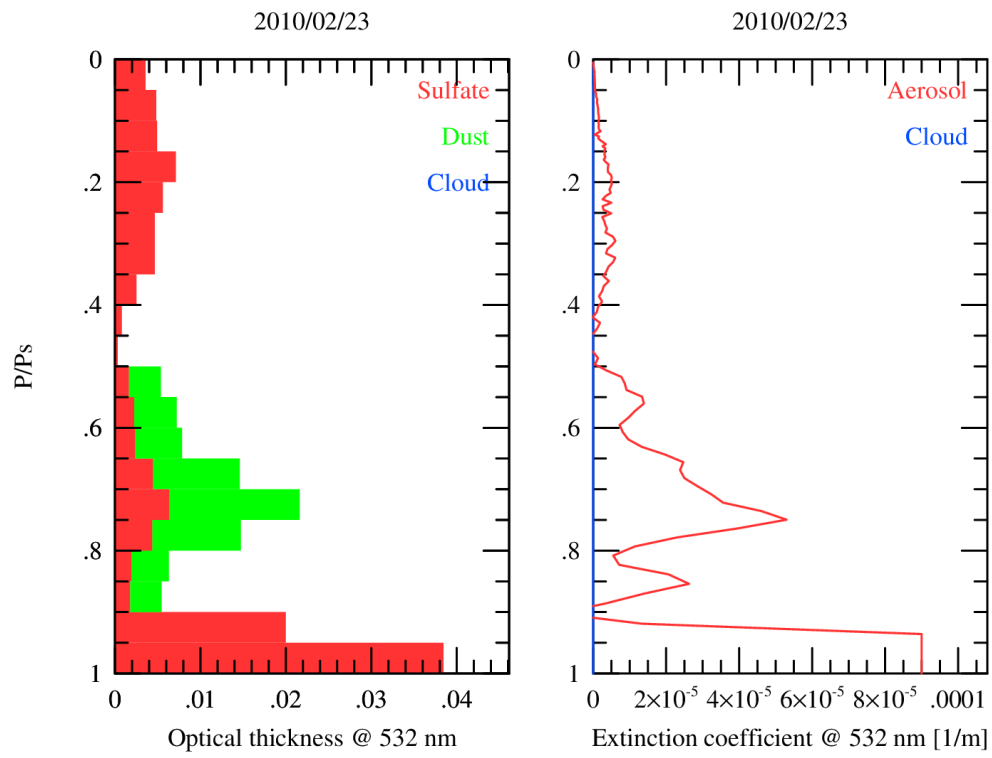


Fig. 4.

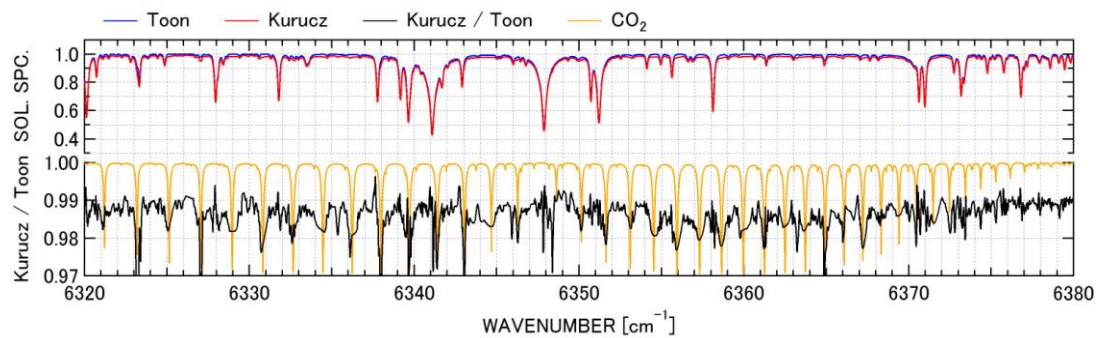


Fig. 5.

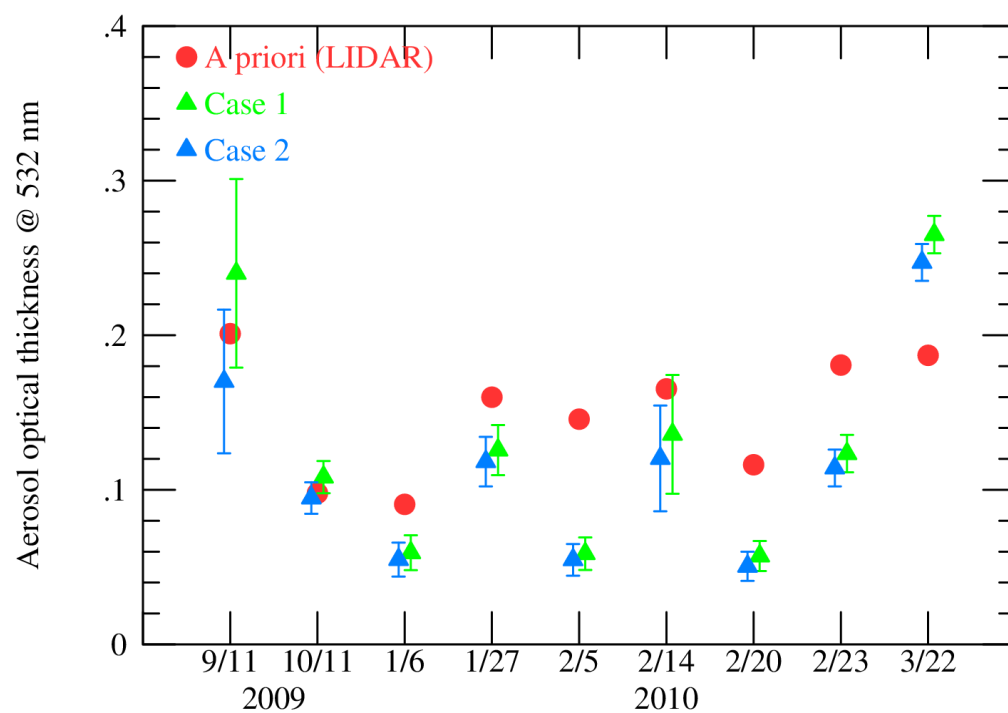


Fig. 6.

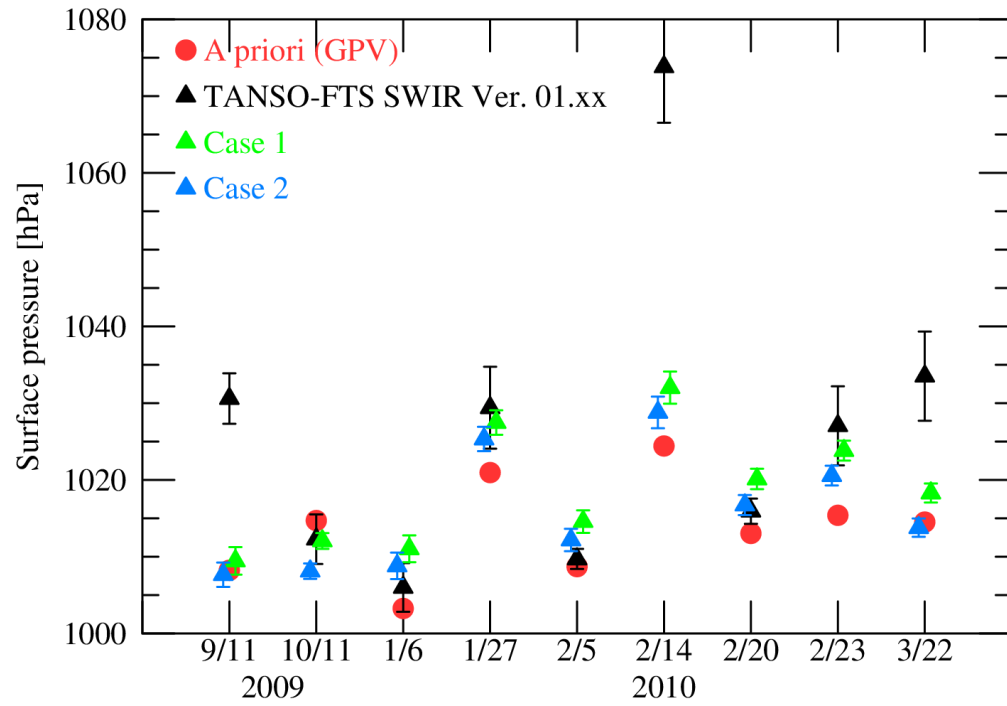


Fig. 7.

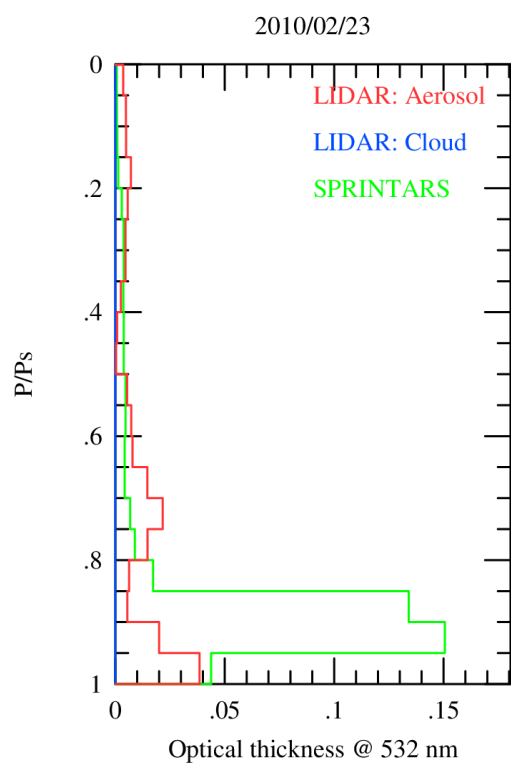


Fig. 8.

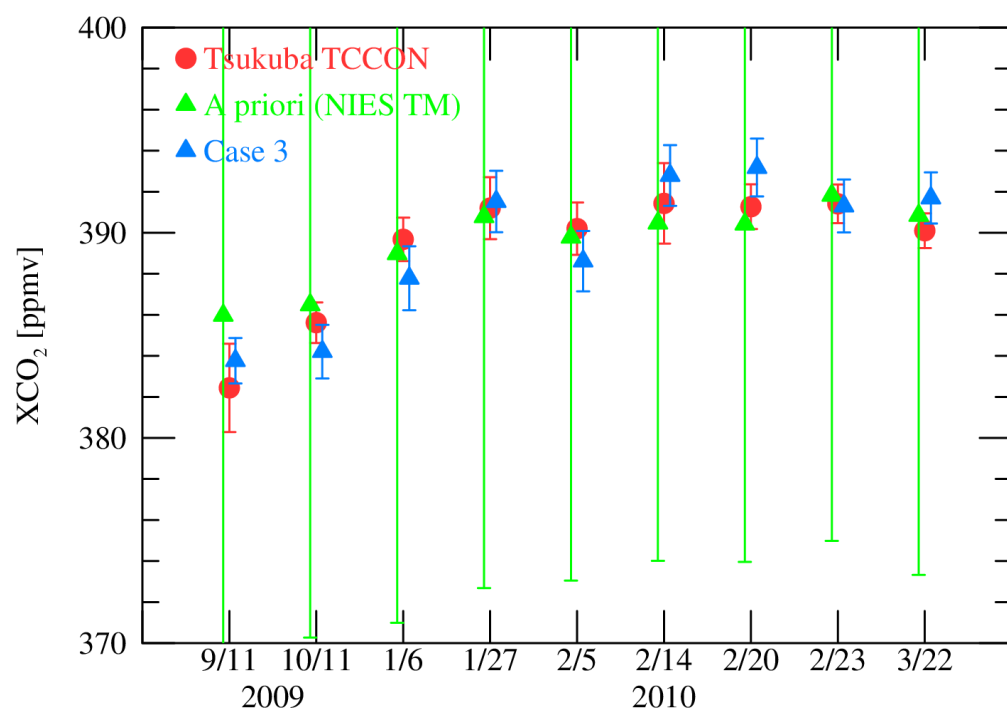


Fig. 9.