Interactive comment on “Regional CO_2 flux estimates for 2009–2010 based on GOSAT and ground-based CO_2 observations” by S. Maksyutov et al.

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Reply to Comments by Anonymous Reviewer 2.

Authors are grateful to a reviewer for review comments and suggestions. As a result we made changes and corrections to the manuscript intended to clarify our presentation.

Replies to the review comments follow:

Major Comments

1. *The reduction in the flux uncertainty depends on the a priori error, the observation error, and the Jacobian (G). I would like to see the authors provide more information about the observation errors used in the inversions. As stated on page 29250, "the diagonal elements of matrix C_D, were determined as the standard deviations of GOSAT XCO2 retrievals found in each of the 5 x 5 grid cells in a month." This standard deviation reflects the spatial variability of the CO2 columns within the 5 x 5 boxes as well as the retrieval uncertainty. It is not the same as the observation error specified in Equation (2), which should reflect the statistics of the model-observation mismatch (assuming that the model transport is unbiased and that the mean differences between the model and observations are due to flux errors). How do the observation errors compare with the statistics of the model-observation mismatch? It would be helpful to see maps of the assumed observation errors for the monthly mean 5 x 5 data shown in Figure 6. It would also be helpful to know what is the reduced chi-squared for the assumed observation errors and by how much it is reduced in the inversion. If the reduced chi-square is too small it means that the observation errors are too conservative and therefore the inversion might be underestimating the error reduction. For the ground-based data, on page 29251, the authors explain that they used the statistics of the model-observation mismatch to filter the GLOBALVIEW data, but used the reported GLOBALVIEW residual standard deviation as the observation error. As with the GOSAT XCO2 data, it would be helpful to know what is the reduced chi-squared with this assumed observation error? What was the motivation for tripling the observation error if the reported GLOBALVIEW data record was less than 70% complete? What is the justification for using only GLOBALVIEW sites where the RMS of the model-observation mismatch was less than 2 ppm?*

Reply

An approach using data monthly averaged within a box of a size of a several degrees latitude-longitude for use in satellite based inversions has been established in previous studies (Rayner and O'Brien, 2001; Pak and Prather, 2001; Rayner et al., 2002; Patra et al, 2003). In our study we follow same line. GOSAT data with large single shot errors of around 2 ppm that are exceeding level of transport model errors are not same as most Globalview sites that have RSD values in the range between 0.1 to 1.0 ppm (which is close to model-observation mismatch). One can consider monthly averaging over 5x5 degree grid as a crude replacement for smoothing in Globalview approach, in that case the STD will be a natural replacement for RSD. We also assume that single-shot errors of around 2 ppm are far exceeding the natural variability level for the tropospheric column, which can be roughly approximated by GV RSD values typical for NH mid-troposphere level of 0.5 ppm.

Normally the sites with less than 70% of actual observations are not included due to missing parts of seasonal cycle that may be important. In that case GV provides the data for site that is essentially a climatology which contains knowledge from previous years, so we use it as a weak constraint, although tripling the uncertainty can considered arbitrary.

Transport model performance is not the same for different sites and depends on local conditions. We found the threshold of 2 ppm is a good measure of model's ability to reproduce the site observations. When model-observation mismatch is systematically large it indicates the model has difficulty to reproduce observations due to model's inadequate horizontal or vertical resolution for properly simulating CO_2 at the particular site.

2. *The authors examined the diagonal of the a posteriori error covariance matrices to estimate the uncertainty reduction. If the GOSAT observations are providing additional information to better constrain the flux estimates in particular regions, one would expect to also see a reduction in any covariance between the flux estimates. Since the inversion is done at a coarse resolution, it should be easy for the authors to examine the correlations between the regional flux estimates to see if this is indeed the case. The correlations may also provide insight as to why some poorly constrained regions are showing large departures from the a priori estimate.*

Reply:

Reduction in the covariance between fluxes for different regions (as express by non-diagonal part of the posterior flux covariance matrix) is directly connected to reduction in the diagonal elements of the matrix. It can be shown in case of the inverse problem solution with SVD decomposition (Rayner et al., 1999), where the solution is first found in a basis of the singular vectors and then converted back to the flux space with a unitary transformation. In the space of the singular vectors the posterior flux covariance matrix is diagonal, with amplitudes reduced by adding extra information from the observations with respect to the prior flux covariance matrix. After unitary transformation, which is equivalent to coordinate rotation, back to flux space the reduction of the diagonal and non-diagonal elements happens in parallel, which means there is little new information that can be extracted from changes in non-diagonal elements as compared to the diagonal ones.

3. *The authors invested significant effort in obtaining an optimized a priori forward model, but there is insufficient discussion about the quality of the a priori simulation to enable the reader to properly assess the benefit of combining the GOSAT observations with the GLOBALVIEW data. For example, Figure 10 should include a comparison of the a priori timeseries with the TCCON data. Similarly, Table 1 should give the biases and RMS differences for the a priori, the GLOBALVIEW a posteriori, and the combined GLOBALVIEW and GOSAT a posteriori. The authors state that the a priori bias with respect to the TCCON data is +/- 0.2%, but also acknowledge that site-by-site GOSAT validation revealed a bias in GOSAT XCO2 of -1.20 ppm relative to the TCCON data. So the GOSAT data have a mean bias of about -0.3%, which suggests that the inversion with the GOSAT data should degrade the agreement between the model and TCCON. It is difficult to reconcile this with the suggestion on page 29259 that the addition of GOSAT data to the inversion acts to suppress deviations from the prior in regions where the fluxes are poorly constrained, indicating that the GOSAT data do not contradict the prior flux estimates.*

Reply:

As it was discussed in the paper, ability of the GOSAT data to correct fluxes already constrained by GV is rather limited in the regions where there are GV observations. It also appears that there always some GV observations near TCCON sites, that makes presentation of the Fig 10 a necessary formality with respect to GOSAT data impact, good match here is rather indication of the consistency between model simulation at GV sites and TCCON sites, which is not always easily achieved (eg Belikov et al., 2013a). A modified Table 1 now includes RMS at TCCON sites for both GV and GV+GOSAT cases. Agreement with TCCON suffers minor degradation (0.1 to 0.2 ppm, depending on site) due to addition of the GOSAT data.

As for the effect of GOSAT bias vs TCCON of -1.20 ppm on the inversion results, there appears to be some misunderstanding. On page 29259, line 21-24, it says the GOSAT data is corrected by subtracting the bias. Remaining misfit with GV data is reduced by optimizing the offset, which is a part of the inversion procedure. In the revised manuscript the description of the offset optimization was expanded.

4. *The inferred fluxes are sensitive to biases in the initial CO2 distribution and the authors have tried to account for this, but they have provided only a brief explanation of the approach. On page 29252, lines 6-9, they mentioned that they added two additional columns to the G matrix to adjust the initial conditions with respect to the surface data, and the GOSAT XCO2 data with respect to the surface data. However, G represents the change in the CO2 concentrations per unit flux. It is not clear to me how G is used to adjust the initial model CO2 relative to the surface data? I would like more information about how this is done. How large was the correction on the initial conditions? Is the adjustment to the GOSAT XCO2 described here carried out in addition to the XCO2 bias correction described on page 29253, line 23?*

Reply:

The offset between GOSAT and GV data is an independent control variable which his optimized together with fluxes. The offset is optimized first estimated separately for each month with overlap between GV and GOSAT data and then average value is used as a constant offset in final inverse model application. The description of the pre-optimization step in the manuscript was extended as follows:

"While the first offset between initial field and GV data is set at the first time step of the Kalman smoother, the second one is allowed to vary during initial optimization run where the offset and regional fluxes are optimized simultaneously. As a result we receive a value of the offset for each month which corresponds to best match between GV and GOSAT data. The average value of the offset is then set as constant offset, and analysis is repeated to give the flux estimates."

Minor comments

1. *Page 29241, lines 12-14: Over what period was the model optimized? Was it from 1979-2010?*

Reply:

The simulation period for tracer transport was 2007, while multiyear mean seasonality was used as constraint.

2. *Page 29241, lines 17-22: The authors state that the atmospheric CO2 data used in the VISIT optimization came from GLOBALVIEW, but that the atmospheric CO2 variability was estimated by a transport model. I do not understand this. Was this necessary because GLOBALVIEW is a smooth data product and not actual observations? The authors need to better explain how the optimization is done.*

Reply:

The description was improved. The fluxes simulated with VISIT model are used as input to the transport model to simulate a seasonal cycle of the atmospheric CO_2 at the GLOBALVIEW observation locations. The misfit between simulated and observed (GLOBALVIEW) monthly mean CO_2 concentrations is optimized with Bayesian approach. First the Jacobian matrix is estimated by calculating sensitivity of the simulated monthly concentration to small changes in the VISIT parameters. Then the inverse problem of finding optimal set of parameters is solved for linearized case. The iterations are repeated several times because VISIT model simulated CO_2 fluxes dependence on model parameters is non-linear.

3. *Is there a problem with using the GLOBALVIEW data in the VISIT optimization and then using them again in the atmospheric inversion? It seems that the same information is being used twice in estimating the fluxes.*

Reply:

This is a reasonable preposition not to use same data twice. Unfortunately, VISIT optimization did not achieve perfect simulation at all sites in terms of atmospheric CO_2 seasonally and interannual variation. Moreover tuning was done with a previous version of the transport model due to its computational efficiency. Thus it is still meaningful to use GV data for flux correction.

4. *Page 29250, line 25: Why set a minimum observation error of 3 ppm? As suggested in my major comment #1 above, it would be useful to know how this impacts the reduced chi-square?*

Reply:

A very similar comment was made by the other reviewers (A. Jacobson and R. Nassar). The following is our reply to the comments and shows the basis of our choice:

The validation of the ver.02.00 GOSAT X_{CO2} retrievals have revealed that the mean and the standard deviation (SD) of differences from TCCON references (data collected at 11 TCCON sites worldwide) are -1.20 ppm and 1.97 ppm, respectively. This global-mean SD of the TCCON-GOSAT differences (1.97 ppm) is on the same order as the global, annual average of the 5°×5° grid-box SDs (1.59 ppm). The monthly distributions of the 5°×5° grid-box SDs, shown in Fig. A, indicate the maximum level of stochastic variability in the current GOSAT retrievals, which are approximately 5 ppm (seen over northern parts of North America and Eurasia during summer months and over eastern part of China during winter). Our approach here was that it would be conservative to regard that the precision of the current version of the GOSAT retrievals would not be any better than the level of the TCCON validation SD. Assigning this SD to each GOSAT retrievals as data error was an option, but at the same time it was also necessary to account for those large stochastic variabilities of which coarse-resolution forward concentration simulation would be difficult. Considering these aspects, we decided to use the 5°×5° grid-box SD distributions as a GOSAT retrieval error model, with the minimum data error set to 3.0 ppm that resulted from inflating the TCCON validation mean SD (1.97 ppm) to take into account the estimated forward modeling error of approximately 1 ppm (conceptually similar to the approach employed in TransCom 3 studies, as demonstrated by Gurney et al. (2003)). This way, data errors above the minimum level can account for the large stochastic variabilities.

5. *Page 29254, lines 5-11: The authors should explain how Equation (5) was used in the spatial and temporal averaging of the data. Did they calculate a monthly mean averaging kernel and a priori XCO2 for each 5 x 5 box and then transform the model? Or did they obtain a transformed model profile for each GOSAT XCO2 retrieval and then averaged the transformed model fields?*

Reply:

In the current analysis, the latter approach was used.

6. *Page 29256, lines 22-24: Is the larger uncertainty reduction over the Middle East, southern Africa, and central Asia driven mainly by the greater number of GOSAT observations in these regions? Or are the XCO2 observation errors smaller in these regions, which would lead to greater uncertainty reduction?*

Reply:

The larger uncertainty reduction over those regions were achieved mainly by the greater number of GOSAT retrievals available in those regions.

7. *Table 1: Please explain which model simulation is used. As suggested in my major comment #3, why not also include the a priori and the combined GLOBALVIEW and GOSAT a posteriori statistics in the table?*

Reply:

What is presented in Table 1 is the RMS difference between the TCCON references and modeled concentrations predicted with GV-only posterior fluxes. As explained in the manuscript, the purpose of presenting this table is to indicate the misfits between them are mostly within the range of observational uncertainties. Table B, prepared for the reply to a comment by other reviewer (A. Jacobson), presents the RMS difference between the TCCON references and modeled concentrations based on GV+GOSAT posterior fluxes. Please see our reply to major comment #7 and minor comment on Figure 10 by A. Jacobson as they are relevant to the comment here as well.

8. *Figure 1, top panel: The y-axis in the plot of the fields at Mauna Loa is too compressed. Why not plot this between 365 - 385 ppm so that the reader can better see the two lines and assess their agreement?*

Reply:

The figure was not intended to be used for quantitative assessment, and the online version can be zoomed to see necessary detail. We hope to provide more comprehensive presentation of the optimized fluxes comparison in the paper by Saito et al, 2013

9. *Figure 10: Please include the a priori CO2 in the comparisons.*

Reply:

Inclusion of the a priori CO2 would make impression that inversion does a better job than it actually does, because a priori diverts from the observations due to global trend mismatch unless proper prior flux adjustment is done before inversion. Figure 10 was presented in the context of showing how valid the GV-based reference CO_2 field (independent of GOSAT observations) that was used to evaluate the spatiotemporal changes in the global distribution of GOSAT X_{CO2} concentrations. The focus and objective here may be diverted if the prior-flux based CO_2 concentrations were overlaid onto the figure and thereby confusing the audiences. We hope that the reviewer understand this point.

10. *Figure 11: Please add a more descriptive caption that explains what is the reference XCO2 concentration field.*

Reply:

We modified the figure caption as follows:

"Monthly-mean GOSAT X_{CO2} retrievals in 5°×5° grid cells minus corresponding reference X_{CO2} concentrations. The reference X_{CO2} concentrations used here were obtained from the result of forward concentration simulation with NIES-TM based on the a posteriori fluxes estimated from GV data alone."

11. *Supplementary information: It would be useful to others in the community who might be interested in comparing their results to those presented here if the authors would include a table in the supplementary material that gives the a priori and a posteriori (GLOBALVIEW and the combined GLOBALVIEW and GOSAT) annual mean flux estimates and their uncertainties for all land regions.*

Reply:

Annual mean flux estimates for the one-year period (June 2009 - May 2010) are shown in Chapter 4 (page 29260, lines 1-5). A campaign for inter-comparing GOSAT-based flux estimates, lead by S. Houweling of SRON, Netherland, is indeed underway in which multiple inversion results, including ours, are being cross-examined. The major outcomes of the research will soon be reported elsewhere.

References:

Pak, B. C., and M. J. Prather, CO_2 source inversions using satellite observations of the upper troposphere, Geophys. Res. Lett., 28, 4571– 4574, 2001.

Rayner, P., Enting, I., Francey, R. and Langenfelds, R.: Reconstructing the recent carbon cycle from atmospheric CO_2, $\delta^{13}C$ and O_2/N_2 observations. *Tellus* **51B**, 213–232, 1999.

Rayner, P. J., R. M. Law, D. M. O'Brien, T. M. Butler, and A. C. Dilley, Global observations of the carbon budget, 3, Initial assessment of the impact of satellite orbit, scan geometry, and cloud on measuring CO_2 from space, J. Geophys. Res., 107(D21), 4557, doi:10.1029/2001JD000618, 2002.