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.

S. Maksyutov
shamil@nies.go.jp

Reply to comments by A. Jacobson

Authors are grateful to Andy Jacobson for his review comments and suggestions. As a result we made several changes to the manuscript intended to clarify our presentation.

Replies to the review comments follow:

Major Comments

1. *Empirical bias corrections of GOSAT retrievals are a potential source of error in inversion systems, and the globally-uniform 1.2 ppm bias correction used here requires careful attention. At the very least, we need to know how the bias correction differently impacts the categories of GOSAT observations: glint-mode over oceans, high-, and medium-gain observations over land. There is also a question of whether there are major geographical variations in the factors causing such bias: land vs. ocean, temperate vs. tropical latitudes, differing aerosol and cloud regimes. Should there prove to be systematic geographic or geophysical variability in the bias, then there are two implications. The first is that the statistical model for retrieval errors cannot be considered independent observations, since the errors driving such non-random errors are presumably dependent upon one another. Even the inflation of GOSAT errors to about one order of magnitude larger than the GV errors, as is done here, is insufficient to handle this problem since the current model insists that all the errors are due to independent stochastic processes. The second implication is that regional flux estimates will be directly impacted by regional retrieval biases. This is a fundamental concern for which I have yet to see good answers, but the current manuscript does not even acknowledge the problem. I'd recommend appropriate sensitivity tests at the very least, perhaps by estimating independent bias corrections for glint, high-, and medium-gain retrievals, or for different geographic and seasonal subsets of the retrievals.*

Reply:

It is possible to derive a regression model similar to Wunch et al, 2011b using TCCON data, and there are reports that application of the derived corrections leads to improving consistency between surface-based observations and GOSAT retrievals, but it was not yet been done for NIES L2 product. We added the following text to section 3.1

"Wunch at al., (2011b) made progress in understanding the spatial and temporal structure of the biases in retrievals with an empirical regression model based on few variables such as aerosol optical depth, airmass along light path and other parameters. However the derived bias estimates are difficult to extrapolate globally due to limited coverage of the TCCON network, thus we had to limit the bias correction to a globally constant value."

2. *When describing the terrestrial and oceanic CO2 prior flux models, characterizing the mean flux, its spatial distribution, and the seasonal and interannual variability represented by the odels is vital. We have only the long-term mean from the Valsala ocean flux model (with its map), not its ENSO signal, long-term trends, or seasonal cycle. Does the Takahashi climatological influence dampen (and bias due to its exclusion of El Nino year data) any ENSO variability?*

Reply:

In the given form of OTTM fluxes, we have shown the 2009-06-2010-05 fluxes with its seasonal cycle in the bottom panel of the Figure 2. Therefore, the seasonal cycle is provided in this way. Since the 2009-2010 transition was of a moderate El Nino year, the OTTM is expected to have variability, with reduced source from the eastern tropical Pacific. The reviewer is correct in the comment that the interannual variability is not represented in the Figure 2. But, that part as such is not very relevant in the present context, because GOSAT inversion shown in the paper is only for one year from 2009-06 to 2010-05. The long term trends become another unresolved aspect from this limited one year inversion.

OTTM may have suffered slight dampening due to (Takahashi et al., 2009) mean assimilation invariably applied over all the years. But we keep a strategy that the model is constrained to (Takahashi et al., 2009) mean only if the inter annual variances are minimum, and that way, the tropical eastern Pacific is only weakly constrained to (Takahashi et al., 2009) mean. In the attached figure (Fig. D), we provide the interannual variability (anomaly of CO2 flux) for eastern Tropical Pacific region and compare it with the Southern Oscillation Index. The OTTM has correct correlation with ENSO during 2009-2010. During 2009 until December, the eastern Pacific flux anomaly appears as a mild sink of CO2.

Following text was added on OTTM flux validation.

Interannual variability of the ocean-atmosphere exchange simulated with OTTM has been analyzed by Valsala et al., (2012), who found persistent quad pole pattern of CO_2 flux IAV in the North Pacific varying at Pacific Decadal Oscillation (PDO) scale. Valsala and Maksyutov (2013) analyzed the interannual flux variability in the northern Indian ocean. Ishii et al., (2013) compared the assimilated flux dataset with multiple bottom-up and inverse modeling estimates within a framework of RECCAP project (Canadell et al., 2011), and showed that interannual variation of the tropical Pacific fluxes is correlating with atmospheric inverse model estimates.

The VISIT information is limited to that presented in Figure 1, which includes simulated atmospheric observations using a transport model and biomass comparison maps, but not fluxes themselves. This information is required to understand how much flux change from the priors that the inversion system is required to estimate. As an example, it would be very helpful to evaluate the prior models bu comparing with other published flux results, such as those from TRENDY, RECCAP, Transcom, or CMIP5 efforts.

Reply:

Recognizing lack of the VISIT validation information we added following text to VISIT section:

“The VISIT model is under continuing development initially based on Sim-CYCLE model (Ito and Oikawa, 2002). Interannual variability of the global terrestrial carbon cycle simulated with Sim-CYCLE was evaluated by Fujita et al (2003), who mentioned that the amplitude of the interannual variability in Simcycle matches well the amplitude of the observed CO2 trend anomalies while missing a phase occasionally. Biomass, productivity and temporal variation of fluxes simulated by VISIT model were discussed in multi-year and multimodel comparison studies by Ito and Sasai (2006), Ito et al., (2010), Ichii et al., (2010), Ichii et al., (2013), Piao et al., (2013). Current version (v. 3.0) of VISIT fluxes has been evaluated against observations with NOAA flask samples and NIES Siberian observations by Saeki et al., (2013). Saeki et al., (2013) found that VISIT reproduces well CO2 seasonal cycle in Northern Hemisphere. Valsala et al., (2013) looked at the intraseasonal variability of VISIT model fluxes during Indian monsoon season and found it is similar to the intraseasonal variability simulated by Carbontracker (Peters et al., 2007), while there are differences in seasonality.

3. *Given the use of statistical estimation techniques in the creation of the land and ocean prior models, there must be some uncertainty information for those priors that could be used to set the values of the prior error covariance matrix, C_m. Real propagation of errors from those prior uncertainties to the atmospheric inversion would be far superior to the current use of temporal standard deviations.* <u>*Should the authors insist on their current system for assigning C_m values, they should present some justification of why modeled temporal standard deviations would be a reasonable estimate for the statistics of the anticipated flux adjustments.*</u> *For instance, if the prior model tends to have too little interannual variabilty and too small an annual cycle in a given region (as many terrestrial models have), how does its resulting temporal standard deviation in any way represent the statistics of the m values the inversion is expected to generate? Those m values may need to increase the mean sink, increase the magnitude of the annual cycle magnitude, and increase the interannual variability. As an aside, it is not clear whether the current scheme attempts to retrieve off-diagonal elements of the C_m matrix...which it could. There is little justification for the assumption that flux adjustments would be independent from grid cell to grid cell.*

Reply:

In the TransCom 3 CO_2 inversion intercomparison, Gurney et al. (2003) assigned growing season net fluxes (GFNS; the sum of monthly-mean exchanges for months exhibiting net uptake) as terrestrial prior flux uncertainties (GFNS were based on net ecosystem productions predicted by the CASA model). The reason behind it was that the GFNS provide ecologically relevant upper bounds for annual-mean terrestrial flux. For oceanic fluxes, Gurney et al. set the uncertainties as 140% of the climatological net oceanic exchanges, which are approximately double the amount suggested by Takahashi et al. (1999). Our approach of using standard deviations of VISIT NEE (2σ) and OTTM oceanic fluxes is essentially similar to their case in finding reasonable upper limits of naturally varying fluxes and assigning them as boundaries in the flux estimation. Our boundaries reflects natural variabilities in the past several decades (30 years for terrestrial biosphere and 10 years for ocean). These are as far back as our carbon cycle models can simulate currently, and we believe that our estimates of prior flux uncertainties reasonably well represent the upper bounds of naturally-varying fluxes. Table A shows the prior flux uncertainties used in the TransCom 3 inversion studies and those assigned in our study (converted into 22 regional values to match with the TransCom estimates). The two sets of values are reasonably similar to one another.

Regarding the retrieval of off-diagonal elements of the C_m matrix, we are currently working on the development of a stochastic model that represents correlations of source regions. Including this model representation in our flux estimation is one of the subjects of our future research work.

4. *The C_d values used in this study deserve some scrutiny. The GV residual standard deviation is a plausible quantity to use for in situ data since it is a summary of differences between observations and a model of the observations. That statistical model significantly includes low-pass filtered differences between data and the trend-plus-seasonal cycle function fit; that LPF goes a long way towards identifying features that high-resolution transport models might represent. This logic is not present in the use of averaging statistics for GOSAT retrievals. It could therefore be argued that the in situ data error model attempts to represent problems associated with coarse-resolution simulated transport, whereas the GOSAT retrieval error model does not. Perhaps this is mitigated by the strong difference in minimum values for the two types of data, but I'd very much like to hear from the authors how they perceive this issue.*

Reply:

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 call 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.

6. *A significant part of the results involves comparing GV and GV+GOSAT inversions, in part to quantify the impact of satellite information on estimated fluxes. The authors claim that fluxes from the GV+GOSAT inversion are closer to the priors than the GV-alone inversion. This is not surprising, since geographic sampling biases in the GV dataset mean that some regions are much more strongly constrained by in situ data than others. Typically this results in large and potentially unrealistic flux adjustments in under-constrained tropical regions to balance overall atmospheric growth rates. The authors present analyses of uncertainty reduction (UR) and differences in flux adjustments (delta-m-squared) to defend their conclusions. In general, uncertainty reduction percentages are difficult to interpret, since their magnitudes depend so strongly on assumed prior errors. Making this measure relative between the GV and GV+GOSAT inversions further ambiguates the measure and obscures the contribution of in situ data to the final answer. I think it is crucial to show a map of the UR for each of the two inversions relative to the assumed prior, with a straight difference map giving the required information on added constraints from the GOSAT retrievals. The current figure 7 hints at some greater tropical influence for the remotely-sensed data, but seasonal variability in the geographic distribution of GOSAT data may be obscuring the importance of the tropical influence. Can a long-term UR map be shown instead of these four sample months? The histogram of delta-m-squared in figure 13 is not particularly informative. The delta m-squared quantity is not perfectly suited for defending the stated conclusion in part because sign differences in the flux adjustments are destroyed by the squaring. It seems that a direct comparison of the m - m_prior values between the two inversions– perhaps as a scatter plot– would be more informative. Further restricting the histogram to region-months where the uncertainty reduction exceeds a threshold further removes the reader from understanding where and when this effect is most pronounced (those significant region-months could be highlighted as a second color in a scatter plot).*

Reply:

The maps of UR for the GV-only and GV+GOSAT inversion relative to the assumed prior uncertainties are shown in Fig. B. The UR maps (relative to the GV-only posterior uncertainty) for the whole analysis period (2009/06-2010/05) are also presented in Fig. C. The reason behind our proposal of expressing URs relative to GV-only posterior uncertainty, instead of prior uncertainty, was that the choice of prior flux datasets and prior uncertainty models currently vary largely among inverse modelers, and thus URs relative to prior uncertainty may not be a robust measure for evaluating the usefulness of GOSAT data if used in any of inter-comparison studies. When focused on the utility of GOSAT data, the use of URs relative to surface-only posterior uncertainty minimizes that potential ambiguity that comes from the differences in priors and their uncertainties that inverse modelers use.

7. *The* <u>*GV+GOSAT inversion should have poorer agreement with in situ data*</u> *than the GV-alone case. Is that true? Can the authors provide an explanation of this effect?*

Reply:

Given the C_d values assigned to GV values and GOSAT retrievals (as explained in Chapter 3 of the manuscript), the reduced chi-squared for the GV-alone and GV+GOSAT inversion cases (fit of posterior concentrations to GV (in situ) values) turned out to be 0.55 and 0.58, respectively. These very similar chi-squared values are reflective of the fact that the C_d values assigned to GV are nearly one-order-of-magnitude smaller than those assigned to GOSAT retrievals. Therefore, in regions where GVs and GOSAT retrievals both exist (e.g. North American regions), GVs constrained fluxes more strictly than GOSAT retrievals, and fluxes estimated from GV-alone and GV+GOSAT for those regions are nearly alike (associated with low UR values).

Minor Comments

Abstract: *The term "integrated" is used in to describe the inversion system both in the abstract and in the summary/conclusions. I did not find any explanation of why this term is used. Please explain what is integrated, or remove this overly generic term entirely.*

Reply:

The term was removed.

General: *it is not entirely clear what time and space resolutions are used by the various components of the system. In particular, GOSAT retrievals seem to be averaged to 5x5-degree grid cells, atmospheric transport performed at approximately 1-degree resolution, and the flux priors are available at a different resolution. Perhaps a brief statement of how these models are all coupled for the inversion could be included in the methods section.*

Reply:

We extended the flux description to the Transport model section :

“The atmospheric transport was simulated at resolution of 2.5x2.5 degree on 32 vertical levels. The model can use surface fluxes at hourly, daily and monthly temporal resolution and 1x1 degree spatially. The fluxes simulated by surface flux models were converted to 1x1 resolution when necessary. The OTTM model fluxes are converted to monthly mean flux fields. VISIT model is run at 0.5x0.5 degree resolution at daily time step while GPP is simulated with sub-daily (hourly) time step. The VISIT fluxes are converted to 1x1 degree daily fields. GFED and ODIAC fluxes are provided to the transport model at 1x1 degree resolution and monthly time step. The 1x1 degree fluxes are remapped to 2.5x2.5 degree fields inside the transport model."

Page 29237, lines 5-10: *Land use history and the long-term effects of land management practices are implicated in the terrestrial carbon sink, and should be included in this list (cf. Casperson, Pacala et al. Science 2000).*

Reply:

Notice added as advised.

Page 29237, line 15: *It is incorrect to imply that CarbonTracker is a regional CO2 analysis. While it has a regional focus, CT belongs in the category of global CO2 inversion systems. Better examples of regional CO2 analyses–those that must infer a CO2 boundary condition–are available.*

Reply:

The wording was corrected.

Page 29240-1: *Does VISIT know anything about land-use change? Does it have any coupling with the imposed GFED biomass burning fluxes? I.e., how does it react to a particular grid cell having been burned?*

Reply:

Although in landuse change is included in some of VISIT versions it was not included here mostly due to difficulties with acquiring up-to-date estimates of the land cover change. The short/long term effects of the fire disturbances on NPP and respiration are not included.

Page 29240: *There is no diurnal cycle in the VISIT fluxes. Any diurnal covariations of PBL mixing and land surface fluxes is thus not represented in this system. This has potentially significant implications for vertical transport of flux signals to GV observing locations. Since atmospheric transport is already resolved at sub-daily time scales, it remains only to infer a diurnal cycle for the land priors, a suitable method for which is availble in Olsen and Randerson (2003).*

Reply:

Use of daily time step in VISIT is done for computation convenience only, otherwise this version of VISIT (*Ito, 2010*) was developed for analysis of the flux tower data and internally uses hourly time step for photosynthesis rate simulation. As justification for this simplification we use results of studies by *Olsen and Randerson, 2004* who found the early afternoon simulated values with daily fluxes are close to those produced with sub-daily fluxes. Another study by *Patra et al 2008* found little improvement with diurnally varying fluxes over monthly and daily fluxes for simulation of the synoptic scale variability at most continuous observations sites. In future versions diurnal cycle is planned to be resolved in order to reduce the mentioned biases introduced by diurnal dynamics.

Page 29241, line 5: *"were simulated" is repeated.*

Reply:
The manuscript is corrected accordingly.

Page 29241: *I'd like some more information on how VISIT is optimized. This brief overview doesn't do much more than give a pointer to other papers. The present authors have the opportunity to summarize the strengths and weaknesses of the VISIT model learned during this optimization procedure. This is especially important for understanding the application of that model to the present inverse analysis. Does the optimization result in an unbiased prior model for terrestrial fluxes, or is there still work to be done in representing the terrestrial sink?*

Reply:

The description of the optimization is prepared for a separate publication extended.

The model was optimized following approach of (*Nakatsuka and Maksyutov, 2009*). In the VISIT case the number of optimized model parameters increased to 11, and number of ecosystem to 16. As the application of the CO_2 seasonal cycle as constraint led to low biased NPP, the biomass and NPP observations had to be included as additional constraints in order be able to reproduce seasonal cycle of fluxes keeping the NPP and biomass within observed parameter range. Recently Saeki et al., (2013) used same set of fluxes, and confirmed reasonable model performance by comparing the simulations with observations of the seasonal cycle.

Page 29242: *The NDP-088 data have undergone several revisions. Please specify which version of the data have been used.*

Reply:

Dataset v. 2010 was used, and citation corrected accordingly.

Page 29245: *Are aviation fossil fuel emissions emitted at altitude into the transport model?*

Reply:

Aviation emissions are inserted near surface in present version of the transport model.

Page 29247: *As I understand the text, the model uses 6-hourly archived winds and 3-hourly archived PBL depths. What, however, is the time step of the integration itself (line 14)?*

Reply:

Typical time step is 10 min, it is mentioned now in inverse modeling section, where spatial and temporal sampling of modeled field is discussed.

Page 29248, lines 11-15: *Claims that the vertical coordinate choice is responsible for good agreement with observations are made without justification. Perhaps a reference could be supplied?*

Reply:

Plots in a referred paper by Niwa et al 2011 (Fig 8) suggest that use of the isentropic coordinates helps simulating better seasonal cycle in NH free troposphere and gradients near tropopause. More importantly for analysis of the total column X_{CO2}, the model is achieving realistic stratospheric air age of 5-6 years at 20 mbar and above, which is difficult to get with conventional sigma or hybrid pressure-sigma coordinates without substantial effort to tune vertical velocities and increasing number of levels to about 70. Isentropic coordinates are essential for reproducing stratospheric vertical transport, which is very slow, and we know no other choice of the vertical grid in an offline model that can be applied to successfully reproduce stratospheric air age of 5-6 years using only 32 levels. Potential X_{CO2} biases stemming from too fast mixing in model stratospheres are in the order of 0.2 to 0.5 ppm

Page 29250, eqns 2-4: *In all 3 equations, various matrix or vector quantities are sometimes presented without the bold font that is intended to indicate that they are not scalars. Example: m* *in Equation 2 is both bold and non-bold.*

Reply:

We will contact the publisher to fix the appearance of these equations as per the reviewer's suggestion.

Page 29251, line 12: *It is confusing to state that the GOSAT retrieval bias is an optimized parameter, unless it is also specified that this optimization is different from the one used to produce the final flux estimates.*

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.

Page 29252, lines 5-10: *The description here of a pre-optimization step for determining the global 1.2 ppm GOSAT bias correction and corrections to the initial atmospheric CO2 distribution is too brief compared to its significance. I would like to have enough information to evaluate the impact of this step on the following inversions. For instance, it is clear that a single global retrieval bias value was being sought, but it is not clear how many degrees of freedom are represented by the initial condition correction. It is not clear whether GOSAT data were used as optimization constraints. It is not clear the extent to which the resulting posterior estimates in this step are independent from one another. I suspect that they have significant posterior error covariances, because otherwise there would be no particular reason for a pre-optimization step like this.*

Reply:

The suggestion to clarify is indeed useful. The description of the pre-optimization step in the manuscript was extended. The 2^{nd} offset value is driven by a best match between GV and GOSAT data. As mentioned above, the value we use is an average value for whole period. As long as we use a temporarily constant offset there shouldn't be extra flux covariances that could be possible in case of an offset floating from month to month. The alternative ways to set an offset are also possible, such as getting mean misfit between GOSAT data and GV-optimized concentrations at GOSAT observation locations.

Page 29254: *What is GECM?*

Reply:

The term "GECM" stands for the Gap-filled and Ensemble Climatology Mean, which should have introduced to the audience in Line 20 on Page 29250. We corrected the text as follows:

"Cells with three or more X_{CO2} retrievals per month were used. Prior to monthly averaging, large GOSAT X_{CO2} outliers were removed via comparisons with climatological X_{CO2} values, derived from an ensemble of forward simulation results by six different transport models that was nudged to surface-based observations (Gap-filled and Ensemble Climatology Mean (GECM); R. Saito et al., 2011). "

Page 29259: *The symbol of delta-m-squared could be interpreted as delta-of-msquared or as the square of delta-m. The latter is intended, but to be ambiguous it should probably be written (delta-m)ˆ2.*

Reply:

Accurate term here would probably be delta-delta-m, so our version is abbreviation of it to delta-m.

Page 29271, line 19. *The dataset is NDP-088, not NDP-08.*

Reply:

We are thankful for pointing it out. Yes, LDEO data base is NDP-088

Figures 8 and 9: *The color scales should be tightened up (use a smaller range) so that the colors are more saturated. Now they are simply too pale to perceive differences.*

Reply:

We improved the appearance of the figures as per the reviewer's suggestions.

Figure 10: *It is difficult to assess whether the GV or GV+GOSAT simulations is better at representing these TCCON retrievals. Can a statistical summary of the mismatches be presented to quantify the residuals?*

Reply:

We added an extra column to Table 1 that shows RMS difference between TCCON and modeled concentrations based on the GV+GOSAT case. As touched previously in our reply to major comment #7, posterior fluxes estimated for regions where GV sites are numerous (also TCCON sites) are very similar in the cases of GV-only and GV + GOSAT inversion. The small differences between the two sets of RMS differences shown in the table are reflective of that similarity.

Table A: Prior flux uncertainties Unit: GtC/reg./year

ID	Region	TC3	Our study
L01	Boreal N America	0.73	0.81
L02	Temp. N America	1.50	2.20
L03	Trop. America	1.41	2.09
L04	South America	1.23	1.58
L05	Tropical Africa	1.33	2.20
L06	S Africa	1.41	1.87
L07	Boreal Eurasia	1.51	1.60
L08	Temperate Asia	1.73	3.54
L09	Tropical Asia	1.22	1.39
L10	Australia	0.59	0.97
L11	Europe	1.42	1.92
O01	N Pacific	1.16	0.52
O02	W Pacific	0.71	0.35
O03	E Pacific	0.79	0.41
O04	S Pacific	1.72	0.29
O05	Northern Ocean	0.37	0.16
O06	N Atlantic	0.56	0.24
O07	Trop Atlantic	0.56	0.19
O08	S Atlantic	0.68	0.15
O09	Southern Ocean	2.12	0.39
O10	Trop Indian Ocn	1.05	0.32
O11	S Indian Ocean	0.76	0.24