Atmos. Chem. Phys. Discuss., 15, C3546–C3557, 2015
www.atmos-chem-phys-discuss.net/15/C3546/2015/

Atmospheric Chemistry and Physics Discussions

Interactive comment on "Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals: a real phenomenon or an artefact of the analysis?" *by* L. Feng et al.

L. Feng et al.

lfeng@staffmail.ed.ac.uk

Received and published: 12 June 2015

We thank David Baker for the detailed and constructive comments. We have carefully read the comments, and make changes accordingly in the revision. Below we address all comments (marked by italics) raised by the reviewer.

This manuscript examines the finding that annual CO2 uptake across Europe is generally larger in inversions that assimilate column CO2 concentrations from the GOSAT satellite than in those that do not. Specifically, as stated in the title, it hopes to determine whether this uptake is "a real phenomenon or an artefact of the analysis". The

main artefact of concern would be potential biases in the GOSAT XCO2 retrievals. However, since this is a global atmospheric flux inversion, other artefacts are also possible here: how random measurement errors and transport model errors interact with seasonally-varying GOSAT data coverage and precision to give errors in the net flux for Europe. And, since we are comparing the GOSAT flux estimates to those from a reference case based on in situ and TCCON data, similar errors could occur in that reference as well. If the difference between the GOSAT estimate and the non-GOSAT reference is due mainly to errors in the reference inversion, the increased uptake due to GOSAT could be both a true phenomenon and an artefact of the analysis (since the assumption that the reference inversion is correct is no longer the case). The manuscript presents an array of inversion experiments that help clarify the differ- ences between the inversions that use the GOSAT data and those that do not. These experiments are helpful and deserve to be published, to help others interpret their own GOSAT analyses. However, the authors do not seem to have accomplished their goal of determining whether the increased uptake due to the GOSAT data is driving the flux estimate closer to the real fluxes or not. That question is best answered by comparing the modeled concentration results with and without the GOSAT data to independent data, and the authors do do that; however, the two CONTRAIL profiles over Europe examined here do not provide a clear answer, in my view. For publication in ACP, I think the authors must either a) compare to more independent data and show clearly that bringing in the GOSAT data does or does not improve the fit to the independent data, or b) back off from the assertions in the abstract and conclusions that GOSAT biases are responsible for the difference, and that the increased uptake is not real. In either case, the experiments here showing the impact of the GOSAT data (the change from not using it) are helpful and ought to be published âĂŤ it is the conclusions taken from these experiments that must be reworked.

The aim of this paper is to question whether the elevated European uptake inferred from GOSAT data is real or an artefact, because small biases are shown to be able to distort our interpretation of XCO2 retrievals. We agree that without further comparison

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with independent observations, we cannot rule out other possible causes, and further, determine whether elevated European uptake is real phenomenon or not. The same argument can be made for Reuter et al. We have revised the abstract and conclusions following David's and other reviewers' suggestions. Particularly, we state in the concluding remarks:
'Complicated interactions between observations and the assimilation system also mean that our present study does not exclude other possible causes for the elevated European uptake reported by previous research from assimilation of GOSAT data. Instead, it highlights the adverse effects of uncharacterized regional biases in current GOSAT XCO2 retrievals that can attract erroneous interpretation of resulting regional flux estimates. A more thorough evaluation of the XCO2 retrievals using independent and sufficiently accurate/precise observations is urgently required to increase the confidence of regional CO2 flux estimates inferred from space-based observations. . .'

. . .Given that, it is not clear to me that the CONTRAIL data at these two airports really help determine whether the GOSAT data improves or worsen the estimate of the European sink. There is a good bit of other data in Europe that could be used to examine this question, though: other aircraft profiles, mountain-top data, and the European TCCON sites, if they could be left out of the reference inversion and used for the independent comparisons. A more broad-based effort to compare to high-quality, independent data is needed to be able to say whether the increased uptake due to GOSAT is incorrect or not.

We agree that due to model error, unaccounted local sources, and limited model resolution etc., the results from our numerical experiments and the corresponding comparisons with CONTRAIL ascent and descent mole fraction data are not very impressive (lower by 0.5-1.0 ppm during the boreal summer). However, the model is able to capture the observed seasonal cycle and the correlation is reasonable (>0.7). As pointed out by the reviewer, the main aim of the comparison is just to show that assimilation of GOSAT XCO2 outside Europe leads to a higher CO2 inflow into the European region

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at the beginning of 2010. Higher CO2 inflow can, in turn, induce an enhanced European uptake estimate, even when XCO2 data within Europe are not biased themselves. Generally, in-situ only inversions show better agreement with independent aircraft observations than the GOSAT only inversions (Houweling et al., 2015). However, due to limited observational coverage, and unquantified transport errors etc., current model-observation inter-comparisons themselves are not sufficient to discard either GOSAT only or in-situ only inversions.

'. . .Given this non-local link between fluxes and measurements taken far away, it might be worth doing some additional sensitivity experiments to investigate the impact of including M-gain measurements over land and glint-mode measurements over the oceans. Is the increased sink over Europe still obtained in that case? Is it larger or smaller?'

This is a good suggestion. We do not use M-gain or glint observation due to data providers' suggestion or due to the availability of that data (e.g. no glint data for UoL v4). We will include them in our future experiments when we assimilate newer versions of GOSAT data.

'. . .Why that is the case is not entirely clear. Is it because the in situ + TCCON data are given much greater weight in the inversion than the GOSAT data (both in terms of precision and number of data points)? Or is it because the inversion finds it easier to resolve differences between the in situ/TCCON data and the GOSAT data by solving for a measurement bias in place of a flux correction? To resolve the issue of the relative weight in the inversion, it would have been useful for the authors to have included the intermediate case: inverting for both the GOSAT and in situ/TCCON data together without solving for the XCO2 biases. And what does it mean to solve for measurement biases as part of the flux inversion, in the first place? The bias corrections made to the data by the retrieval teams (ACOS and UOL) have used the best available validation data already (TCCON, suites of models). The bias estimates done as part of the atmospheric inversion are then seeking improve the retrieval teams' best bias estimates

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through comparison to the a priori CO2 fields given by the particular models used here: this rolls together the effects of errors in the prior fluxes and transport model, and can lead to XCO2 bias corrections that may have little to do with actual measurement issues. That being said, the biases that are estimated in this approach do seem to have large negative values for Feb-Apr, on the order of 0.5 ppm, at least in Western Europe for the ACOS case. If these bias estimates are correct, they might explain 0.18 GtC a−1 of the larger GOSAT uptake, according to the authors.'

As pointed out by the reviewer, the actual results depend on relative weights given to each type of observations, as well as on the assumed uncertainties for prior flux and bias estimates. More strictly speaking, the derived biases are the systematic differences between model and GOSAT XCO2 retrievals. So in the revision, we have discussed limitations of the joint data assimilations. Also, a further test shows that when no bias correction is used, the uptake inferred by the joint data assimilation experiment INV_ACOS_INS will be increased from 0.62 GtC/a to 0.77 GtC/a (see Section 4). But the most important point is: we infer an European uptake around 0.62 GtC/a by jointly assimilating GOSAT and in situ observations together with a simple bias correction scheme. Those derived monthly biases are varying, and mostly within 0.5 ppm, which is a challenge to study based on the current validation network.

'. . .For example, did they correct the XCO2 data with all 12 of the regional biases estimated in the INV_ACOS_INS and INV_UOL_INS cases, or just the ones for Western and Eastern Europe?'

Only the biases over West and East Europe have been corrected. We have clarified this point in the revised manuscript.

I found these sensitivity experiments helpful for understanding the European sink obtained in the authors' global GOSAT flux inversion results, but I often didn't agree with their interpretation of the experiments and the terminology they used. In the Abstract, they say "We show this elevated uptake over Europe could largely be explained by

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mis-fitting data due to regional biases." Biases in what, the XCO2 measurements? Yes, regional XCO2 biases might explain the difference, but that is not the only possible explanation: the fluxes in the in situ + TCCON inversion might be biased over Europe due to the amplification of measurements errors caused by the sparse spatial density of the measurements, because of errors in representing the in situ data with coarse resolution models, or due to biases in the TCCON data, for example . . .'

The main aim of this paper is to stress that currently we are not certain whether the elevated European uptake is real or an artefact. We show this by highlighting the sensitivity of the flux estimates to possible regional biases within or outside Europe. We totally agree that there are other possible explanations and causes for the elevated uptake as well. We only suggest that regional biases can result in such elevated uptake (while current observation network cannot rule out these small and varying biases). We have rewritten the introduction and conclusion to make these points clearer.

'At the end of the Abstract, "We find a monthly varying bias of up to 0.5 ppm can explain an overestimate of the annual sink of up to 0.18 GtC a−1 " âĂŤ again, the implication is that the large European uptake from the GOSAT data is wrong and that lower uptake from in situ +TCCON data is right. The same point (that the difference could be due to XCO2 biases) could be made using language that doesn't try to argue which estimate is more correct. "Overestimate" could be changed to "larger value", etc. In the "Discussion and Conclusions", the influence of GOSAT measurements outside of Europe on European net fluxes is described as "...a positive model bias of CO2 being transported into Europe, due to the assimilation of GOSAT XCO2 data outside of Europe" and an "elevated CO2 inflow into the European domain". The effect of biased "boundary conditions" and "model inflow" are mentioned, as if a regional inversion is being used. Rather than using this language, perhaps it would be easier just to note that the GOSAT data tend to drive larger uptake in Europe balanced by less uptake in the same northern latitudes outside of Europe, with corresponding lower and higher CO2 concentrations over each area? "Erroneous interpretation of XCO2 data can

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result from analyses if unbiased boundary conditions are not addressed": while this is not completely clear to me, it sounds like the authors are saying that biases in the GOSAT XCO2 data are responsible for the increased uptake, and this has not been established.

See above responses. Both our global and regional inversions in Appendix A suggest that boundary conditions produced by assimilation of GOSAT XCO2 retrievals outside EU will result in significantly enhanced European uptakes, particularly at the beginning of 2010. We agree that because of limited observation coverage and unquantified model transport errors etc., we cannot conclude that GOSAT XCO2 retrievals themselves are biased high or low. It is actually one of our major points that there are not sufficient independent observations to falsify the in situ only inversion or the GOSAT only inversion. We have stressed this in the main text and in the concluding remarks.

In the third paragraph of the "Discussion and Conclusions", I agree with discussion of the estimated XCO2 biases, but I would welcome some more discussion about what a correction to the bias corrections already solved for and removed by the retrieval teams actually means. What is the motivation for it, why is inverting for it as part of the atmospheric inversion possible, what are some of the potential pitfalls?'

The retrieval teams mostly used the co-located TCCON and GOSAT observations to derive bias correlation. Our bias correction scheme is based on the (on-line) comparison between model simulation and GOSAT retrievals, which are able to take into account more GOSAT retrievals to infer monthly biases at regional scale. In addition to the TCCON network, the joint assimilations have used conventional surface observations, and the GOSAT XCO2 data themselves. But there are issues with on-line bias correction schemes, particularly before we are able to properly characterize systematic observation and model errors. In revision, we added discussions on those potential issues in both Section 4 and Appendix A.

In the final paragraph, I agree with the authors that "This study highlights the adverse

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effects of regional biases in current GOSAT XCO2 retrievals that can attract erroneous interpretation of resulting regional flux estimates." However, the way it is written implies that such biases are responsible for the increased uptake when GOSAT data are added to the inversions, and this has not been demonstrated convincingly. Coming where it is at the end of the conclusions, it appears to be answering the question asked in the title: "...is [the increased uptake in Europe] a real phenomenon or an artefact?". If the authors wish to retain this language and implied conclusion, they must bring in additional independent data and show more convincingly that the increased uptake due to GOSAT data worsens to fit to them. If they do not want to take that approach, they should reword the interpretation and conclusions to discuss the shift towards greater uptake, without judging if it reflects reality or not'

We have clarified these points in the revised manuscript to make it clear that while we study the impact of uncharacterized biases on the elevated European uptake there are other possible explanations including that the signal is real (See above responses, and the revised concluding remarks). Our results just stress that more dedicated measurements are required to determine whether the elevated European uptake is real or not.

'Overall, I think the authors have done a nice job on this paper, but they just need to be a bit more careful with their conclusions, explicit or implied. It would be nice if they could show more conclusively that the larger net uptake over Europe is inconsistent with independent data. If that is not possible, a careful rewording of the title, abstract, and conclusions is needed that retains the main thrust of the sensitivity experiments without asserting too much.'

We thank David for this measured assessment of our work. His recommendations together with other reviewer comments have helped us to revise the manuscript.

Some more detailed comments follow:

1. page 1994, line 12: "and the annual variations": It is not clear what field with inter-

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annual variations you are referring to here - land biosphere? Land + ocean + fossil fuel +biomass burning? Please clarify.

We have rewritten the paragraph in section 2 to provide more details about our a priori error covariance.

2. p 1994, L 13: The global CO2 fluxes often have large temporal and spatial correlations, such that the global uncertainty from an inversion may be small, while at the same time smaller-scale flux uncertainty can be quite large. Do you account for any such correlations in doing the global uncertainty scaling mentioned here? What is the percent uncertainty on the land biospheric fluxes after this global scaling? (That is, how different is it from the initial 70% that you mention?)

Following our previous study (see Chevallier et al., 2014), we have included a spatial error correlation with a correlation length of 800km for land, and 1500 km for ocean in our prior errors. We have also included a temporal correlation with a correlation length of 1 month. The rescaling is applied to aggregated annual global land and ocean errors after taking into account these correlations. We have added this information in the revised manuscript (see above response).

3. p 1995 L 8-11: for comparison, please also give the bias with respect to the HIPPO measurements given by the INV_TCCON case - how much better was it in that case, globally?

For INV_TCCON, the bias against HIPPO-3 is about 0.05 pm. We have added this information (and new figure 2) in the revised manuscript.

4. p 1995 L 15: Judging from Figure 1, it would seem you are discussing the results for June 2010 rather than July.

Thanks for spotting this mistake. Yes, it is for June. We have corrected this mistake in the revised manuscript.

5. p 1995 L 18-24: This point that the GOSAT-only inversions result in the largest

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uptake compared to the in situ/TCCON case in early Spring / Winter is important - it contradicts the idea that the GOSAT data cannot drive large changes from the prior in winter when coverage at high latitudes is poor.

This is an interesting result. Such large uptake is also found in experiments by Chevallier et al., using a variational approach.

6. p 1996 L 13-15: "...indicating an overestimate in the CO2 transported into the European region in GOSAT inversions. This highlights the sensitivity of the European flux estimate to lateral boundary conditions." Another way of saying this is that large deviations of flux in Europe in the inversions tend to be anti-correlated with flux deviations outside of Europe at similar northern latitudes. This is a consequence, apparently, of the a posteriori flux uncertainties still being rather high at the scale of large regions like Europe in the GOSAT inversions.

We agree, and modification is made to stress that at that season, Europe is poorly constrained.

7. p 1996 L 24: replace "with a model" with "with those from a model"

Change made following the suggestion.

8. End of p 1996, beginning of p 1997: You seem to be discussing results shown in Figure3, but you do not mention that figure here. Maybe mention Figure 3 here?

The corresponding figure has now been mentioned.

9. p 1997 L 16: Consider replacing "we add 0.5 ppm" with "we add a bias of +0.5 ppm". When I first read this, it was not clear to me whether you were adding a bias to the data, or increasing the assumed measurement uncertainty by 0.5 ppm.

Change is made to clearly say that a bias of + 0.5 ppm has been added.

10. p 1997 L 24: "...to quantify systematic bias" - bias in what? Fluxes or measurements?

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We change the phrase to: to estimate systematic bias in XCO2 retrievals.

11. p 1997 L 24: "online": It is not at all clear what you mean by this here. With some work the reader eventually will piece together what you mean, but maybe you can reword things a bit to make it easier. "On-line" = solving for biases as part of the inversion; "off-line"=deducing biases via comparisons of a posteriori modeled CO2 fields and XCO2 data.

Thank for suggestions. We have revised the Section 4 to clarify the meaning of 'on-line', where observation biases are estimated together with regional fluxes from joint assimilation of GOSAT and in situ observations.

12. p 1998 L 3-4: "the main advantage of our online bias estimation is that the uncertainties associated with errors in flux estimates can be taken into account." In what, the bias estimation procedure? Does "uncertainties" refer to the bias estimate? Or the flux estimate? Please reword for clarity.

It is for the uncertainty in model CO2 concentrations caused by errors in flux estimates. We have rewritten the paragraph in the revision.

13. p 1998 L 4-5: "To investigate the spatial pattern of the XCO2 biases within Europe, we split Europe into West Europe..." This is for the purposes of solving for the measurement biases, right? Maybe say so more explicitly.

Changes made to clarify that we are solving for sub-region observation biases.

14. p 1998 L 8-9: Please put minus signs on the European flux values - you don't refer to them as "uptakes", but rather "fluxes", so we need the sign.

We agree, and change them to 'European uptake' to avoid confusion.

15. p 1998 L 15-16: "...We find that after correcting for these biases the annual European uptake estimate from INV_ACOS is reduced by 0.18 GtC a−1 ": It is not clear where you got this 0.18 GtC a−1 figure from. If I take the difference of the values for

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the INV_ACOS_INS and INV_ACOS cases from Table 1, I get: -0.61 - (-1.20)=+0.59. Is this correction for the biases done with some additional inversion or forward run not mentioned in Table 1? Or are the values in Table 1 for the INV_ACOS_INS case done without the biases being estimated in the state (in addition to the fluxes)?

Yes, we have made an extra GOSAT inversion experiment after the derived XCO2 biases over West and East Europe were corrected. This is described in the revised manuscript.

16. p 1999 L 4-5: "...is determined by a positive model bias of CO2 being transported into Europe": This language doesn't help clarify the experiments, in my opinion. What the experiments show is that inversion of GOSAT data outside of Europe cause large uptake in Europe counterbalanced by a decreased uptake outside of Europe. I don't think "bias" or "transport" need to be brought up to make this point.

To make this point clearer, we have included extra experiments in Appendix A. We found similar enhanced uptake at the beginning of 2010, when a posteriori fluxes from GOSAT inversion INV_ACOS are used to produce the boundary conditions for quasi-regional inversions, where only ACOS observations within Europe are assimilated. So we change the sentence as:
'... appears to be related to the systematically higher model CO2 mass being transported into Europe, due to the assimilation of GOSAT XCO2 data outside the European region.'

Interactive comment on Atmos. Chem. Phys. Discuss., 15, 1989, 2015.