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Interactive Comment

Interactive comment on "Regional-scale geostatistical inverse modeling of North American CO_2 fluxes: a synthetic data study" *by* S. M. Gourdji et al.

S. M. Gourdji et al.

amichala@umich.edu

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Responses to Comments from Referee #2

The authors thank the reviewer for his/her thoughtful suggestions to improve the quality of the manuscript. Please refer to responses to Referee #1 for overall broad-scale changes that will be made to the revised manuscript based on comments from both referees. Responses to individual comments from Referee #2 are included below. (Original referee comments are in italicized text.)

"This study investigates the optimal set-up of a geostatistical inversion system for the estimation of regional sources and sinks of CO2. It is a very systematic, statistically sound piece of work. The experiments are highly relevant steps that need to be taken before a system can be exposed to real data. In this sense the methodology could serve as a good example for other studies. However, it remains at a rather technical level. It is difficult to get a feeling for the importance of the results, the extent to which these findings were to be expected in light of previous studies and how the performance of the optimal set-up compares with what others have published before using different methods. More emphasis on these aspects would make it more useful to a wider group of scientists than experts in geostatistics only. "

We believe that the results from this manuscript are relevant not only for people doing geostatistical inversions, but also for a broader community of inverse modelers using continuous, continental measurements in regional inversions. However, the authors agree that the discussion paper was overly technical, with so much detail as to make the paper accessible to only a narrow audience. The broad revisions to the manuscript described in the responses to Referee #1 will hopefully help to make the paper easier to follow, and the main conclusions from the analysis should also be clearer and more relevant to a wider audience of carbon cycle scientists. Finally, the broader relevance of the study will be stressed in the introduction, discussion & conclusions sections of the revised manuscript.

"Several of the comments and suggestions made below are meant to make the manuscript easier accessible. I personally experienced some difficulty understanding the terminology. Some more work will be needed in these directions as explained in further detail below. Besides this, however, in my opinion there is no fundamental problem that should prevent final publication.

ACPD
9, C11993–C12001, 2010

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Discussion Paper

GENERAL COMMENTS

It is difficult to judge the overall performance of the inversion without definition of a requirement for a regional inversion for Northern America from the perspective of carbon cycle research. "

Ultimately, with an expanded measurement network (at least in North America and Europe), the hope would be that regional grid-scale inversions could approach the scale of estimation of biospheric models (i.e. 1°x1°). Yet even at slightly coarser scales, a geostatistical inversion relying solely on the atmospheric data constraint can provide an independent set of fluxes useful for evaluating bottom-up model output. In fact, the atmospheric data tends to provide a relatively diffuse signal, and it is not yet clear in the literature at what scales continuous, continental measurement data can help to constrain fluxes in regional inversions. The current revised manuscript hopes to make a contribution towards answering this question, particularly in the discussion section which focuses on the ability of the inversion to infer eco-region scale fluxes with and without transport error. (Grid-scale fluxes can only be interpreted to a limited extent, given that they have such high uncertainties that most are not significantly different from zero.) Also, the current study uses only 9 towers to constrain fluxes across all of North America. The finest recoverable scale from a regional inversion should be related to the density of the measurement network, and this will be explored in future work taking advantage of data from new measurement towers that have come online since 2004. These points will be further clarified in the revised introduction and conclusions.

"Right now only some vague suggestions are made that this simple set-up is performing reasonably well already. It is not easy to judge the value of an estimate within 10% for North America on the basin of an inversion, that, if I understand correctly, only represents a temporal aggregation error on the side of the data uncertainty (it was not clear to whether or not the results in figure 6 and 9 included transport error, which makes me assume this is not the case)."

ACPD

9, C11993–C12001, 2010

Interactive Comment

The results in Figures 6 and 9 from the discussion paper did include both temporal aggregation and simulated transport error in the observations and model-data mismatch covariance matrix. However, the authors agree that we should clarify what we mean by "performing well", and further discuss at which spatiotemporal scales we are inferring reasonable fluxes from the inversion. The revised manuscript will show inferred fluxes using setups with both "perfect transport" (i.e. temporal aggregation error only) and simulated transport error. With perfect transport, we will show that the cases resolving the diurnal cycle on the flux side are able to estimate relatively accurate eco-region scale fluxes that mostly fall within the 95% confidence intervals. The skill of the inversion is reduced with transport error, such that only the continental-scale flux is reliably estimated, with most eco-region scale fluxes remaining closer to the mean continental flux. As mentioned previously, we expect this situation to improve with corrections for systematic errors in the transport and boundary conditions, as well as with an expanding measurement network.

"In the abstract it is mentioned that the results are likely applicable to other inversion methods. It is not clear why this should be the case. Actually it is not even clear how robust the findings are to the specific set-up that is chosen for the presented geostatistical inversion. For example, Figure 5 indicates that the relative performance of the cases depends quite a bit on the treatment of transport model uncertainty. If those errors are accounted for the difference between the cases doesn't look that big. What about its significance? The question arises how relevant the discussion on flux and data aggregation really is for a real-world application in which systematic transport model uncertainties are likely to dominate the error budget. The question of robustness is important because it is chosen to perform these simulations in a simplified inversion set-up."

The simplified inversion setup presented here is designed to help isolate different components of regional inversions which may contribute to overall errors in a real data en-

ACPD

9, C11993–C12001, 2010

vironment. In terms of whether the results are applicable to other inversion methods, the question of which data averaging and estimated flux time periods to use should be relevant for any regional inversions using continental, continuous data with strong diurnal and synoptic variability, given that aggregation errors are relevant for all inversions, regardless of method. (However, synthesis Bayesian inversions estimating the residual from a diurnally-varying biospheric model may be less subject to temporal aggregation error. This point will be clarified in the manuscript.)

The issue of transport error and how it affects the skill of the inversion should also be relevant for inverse modelers regardless of method. It is true, in the current study, that if realistic amounts of transport error are accounted for, the differences between the cases don't look very substantial. This is most likely due to the fact that the representation of transport error in this study as random noise reduce the skill of the inversion in such a way that the fluxes remain relatively close to the mean across all cases. It remains to be seen how non-random transport error affects the skill of the inversion, or how improvements in transport modeling and boundary condition simulation could help to rectify this situation. Regardless, the analyses in this paper point to underlying issues in using continuous, continental data in regional inversions, which may be masked by the currently high levels of model-data mismatch from transport model error and errors in the boundary conditions. As transport errors hopefully decrease in magnitude in the future, the issues with temporal aggregation error will still be an issue for regional inversions.

The points discussed here will be included in the introduction, discussion and conclusions of the revised manuscript.

"On page 21 it is mentioned that transport errors destroy the skill of the inversion in estimating the Q covariance parameters. How then do you explain that the posterior uncertainty and the extent to which it represents the true uncertainty is almost not

affected by accounting for transport model error (as shown in table 5)?"

The inversions with transport error presented in Table 5 and Figure 5 of the discussion paper used the "true" covariance parameters in **Q**, and did not use the results of the RML-Inv tests described on page 21 (with or without transport error). Therefore, these inversions were not affected by the problem using RML-Inv to estimate parameters with transport error. However, even with the "true" **Q** parameters, the inferred RMSE of the fluxes did go up with transport error included in the observations, but the uncertainties also went up, such that roughly 95% of the true fluxes were still contained within the 95% confidence intervals. The cases in the discussion paper presented with refinements to the covariance matrices in Figures 6, 7 and 9 did use the RML-Inv parameters, although without transport error. These inversions should more accurately have used RML-Inv results with transport error, and this will be corrected in the revised manuscript.

Overall, the authors agree that the assumptions corresponding to each set of presented results was confusing in the discussion paper. In the revised manuscript, a number of changes should help to address this. First, the results of RML-Inv will be presented with and without transport error. Also, two sets of inversion results will be presented with and without transport error, and these inversions will use the appropriate corresponding set of RML-Inv parameters. Captions to tables and figures will be appropriately labeled to indicate what is being presented.

"SPECIFIC COMMENTS

Page 9, equation 4: How do you obtain beta-hat?"

The equation for beta_hat is as follows:

$$\widehat{\beta} = \left(\mathbf{X}^T\mathbf{Q}^{-1}\mathbf{X}\right)^{-1}\mathbf{X}^T\mathbf{Q}^{-1}\,\mathbf{\Lambda z}$$

ACPD

9, C11993–C12001, 2010

This equation will also be added to the text.

"Table 1: This table doesn't provide much information. The text lists several more differences between the inversion cases than mentioned in the table. (such is a longitudinally varying drift factor, difference in the number of drift factors etc). It would be useful to have a table that summarizes all the differences between the inversion cases."

We will add more columns to the revised table to summarize all differences between the 3 new cases. This table will show the difference in flux resolution for each case, as well as corresponding differences in the structure of the trend in **X** and the flux covariance matrix **Q**.

"Section 3.1.2: The first paragraph mentions that the skill of the inversion to recover the temporal aggregation error and transport model error is tested. In didn't find that back anywhere in the results. "

It was briefly mentioned in the text that these tests (i.e. RML-Inv for temporal aggregation error and random transport noise) performed well (p. 22428, lines 3-7), although this should have been further clarified in the text. In the revised manuscript, we plan to present the results for RML-Inv, as compared to the true parameters, for both **Q** and **R** parameters in Table 3. This table will also show results with and without transport error.

"Table 4 and 6 list inversion inferred transport errors. From the text I learned that this is the estimate refers to the "true" transport error (which I think should have been mentioned in the table caption too). "

These "true" transport errors represent the residual model-data mismatch present in the real measurements after accounting for temporal aggregation error. They are derived by subtracting model-data mismatch variances inferred with synthetic data from

ACPD

9, C11993–C12001, 2010

that inferred with real data. Because we expect the "real" model-data mismatch to include transport, aggregation and measurement errors, whereas the synthetic model-data mismatch to contain only temporal aggregation errors, their difference presents an overall estimate of the magnitude of "true" transport error. (Measurement and other types of errors are assumed minimal.) A short statement to this effect will be added to the table captions.

"Also in the caption of figure 3 and 4 it helps to remind the reader whether we are dealing with inversion recovered or "true" aggregation errors and that these are errors in the simulated concentration due to temporal aggregation of fluxes."

We plan to remove these figures from the revised manuscript. The revised Table 3 will show the "true" temporal aggregation errors for each tower in the **R** matrix, as compared to the values inferred using RML-Inv with the synthetic measurements. The discussion of this table will describe the differences in the true vs. simulated values, and will also provide a better definition of temporal aggregation error.

"Table 5: It is mentioned somewhere in the text, but it helps to remind the reader in the title that the numbers refer to 8-day fluxes."

Thank you. As mentioned in the responses to Referee #1, we will be comparing inversion results at the monthly scale, rather than the 8-day scale in the revised manuscript. However, all tables and figures presenting inversion results will include a modification to the caption to indicate the temporal scale of comparison.

"Page 26, line 25: What is the meaning of a negative transport error? This should briefly be clarified."

This was an artifact of keeping the **Q** parameters constant while optimizing for the **R** parameters in the discussion paper. This was also related to our rather rough method

ACPD
9, C11993–C12001, 2010

for inferring transport error magnitudes, where the inferred “real” model-data mismatch ended up slightly lower than the synthetic data value for one tower. In the revised manuscript where we estimate **Q** and **R** parameters simultaneously, we no longer infer negative transport errors.

“Page 23, line 1: “discussed, . . . shown in Figure 3” I see no “non-afternoon measurements” in Figure 3 . . .”

Thank you. This should have been Figure 4. However, as previously mentioned, we plan to remove this figure from the revised manuscript with the accompanying text.

“TECHNICAL CORRECTIONS

Page 23, line 2: ‘except for with exceptions”’

Thank you. This line will be removed from the revised manuscript as mentioned above.

“Figure 3: 5 instead of 6 cases”

Thank you. This should have said 5 cases, and then mentioned that the F3h/C3h case technically has zero temporal aggregation error for this synthetic data setup. Again, this figure will be removed from the revised manuscript.

ACPD
9, C11993–C12001, 2010