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Interactive Comment

Interactive comment on "Investigation of error sources in regional inverse estimates of greenhouse gas emissions in Canada" *by* E. Chan et al.

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General comments: (1) This study used fossil fuel CO_2 emissions as target. However, CO_2 also has land and ocean sink, and land-use change emissions, which are significant compared to fossil fuel CO_2. This study did not account for these emissions. This study used the CarbonTrack simulation as the synthetic observation which probably has accounted for all emissions and sink (right?), while the FLEXPART simulation used for the inversion did not account for the land and ocean sink (right?), which would lead to a mismatch between the simulated concentrations by FLEXPART and CarbonTracker. This is major issue that hinders the robustness of the interpretation of the

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"posterior error" and mismatch between the obs and simulation.

Authors' response:

The authors would like to thank Referee #2 for the comments. The major concern of not including CO_2 fluxes from 'land (biosphere) and ocean sink, and land-use change emissions' is similar to the comment from Referee #1. The main objectives of this study are to examine the impacts of errors from the optimisation method, prior flux distribution and the atmospheric transport model, as well as their interactions on inverse flux estimates under a series of controlled experiments. We did not mean to make any claims that the inversion could work for biospheric CO_2 with the current setup. We apologize for any confusion.

We began with the simple case of slowly varying (monthly constant) positive fluxes (no sinks) of CarbonTracker fossil fuel CO_2. The results should be useful for inversion of emissions with similar spatial and temporal characteristics as fossil fuel CO_2, e.g. wintertime CH_4 in Canada with mainly fossil fuel, agriculture, landfill emissions and essentially no wetland emissions or possibly in urban areas where the contributions from biospheric CO_2 are relatively insignificant. We will clearly state this limitation in the abstract and the introduction section.

Performing biospheric CO_2 flux inversions represent the next level of complexity and would require using prior fluxes with strong diurnal variations and both positive and negative fluxes. It merits a separate study to examine the errors and uncertainties for this case, we plan to examine the different components of errors for regional biospheric CO_2 flux inversion shortly.

We only used the fossil fuel CO_2 concentration component from Carbon-

Tracker and similarily we only folded fossil fuel CO_2 fluxes to FLEXPART to calculate our prior modelled concentrations to avoid any flux source mismatch in our pseudo-observation experiments.

Revised abstract

Inversion models can use atmospheric concentration measurements to estimate surface fluxes. This study is an evaluation of the errors in a regional flux inversion model for different provinces of Canada, Alberta (AB), Saskatchewan (SK) and Ontario (ON). Using fossil fuel CO_2 CarbonTracker model results as the target, the synthetic data experiment analyses examined the impacts of the errors from the Bayesian optimisation method, prior flux distribution and the atmospheric transport model, as well as their interactions. The posterior fluxes were estimated by the Markov chain Monte Carlo (MCMC) simulation and cost function minimization (CFM) methods. Experiment results show that the estimation error (or relative percentage difference between the posterior and target fluxes i.e. ((posterior flux - target flux)/target flux)*100%) increases with the number of sub-regions using the CFM method but not for MCMC. For the region definitions that lead to realistic flux estimates on the sub-regional and monthly scale, the numbers of sub-regions for the western region of AB/SK combined and the eastern region of ON are 11 and 4 respectively. The corresponding annual flux estimation errors for the western and eastern regions using the CFM method are 0% and 8% respectively, when there is only prior flux error. The estimation errors increase to 40% and 232% resulting from transport model error alone. When prior and transport model errors co-exist in the inversions, the estimation errors become 29% and 201%, whereas the estimation errors using MCMC are considerably smaller. This result indicates that flux estimation errors are dominated by the transport model error and different sources of errors can potentially cancel each other and propagate

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to the flux estimates non-linearly. Although estimation errors can be reduced, increasing the number of sub-regions beyond 11 sub-regions for AB/SK and 4 sub-regions for ON can produce unstable monthly and unrealistic fluxes.

In addition, it is possible for the posterior fluxes to have larger differences than the prior compared to the target fluxes, and the posterior uncertainty estimates could be unrealistically small that do not cover the target. Stable and realistic sub-regional and monthly flux estimates for western region of AB/SK can be obtained, but not for the eastern region of ON. This indicates that it is likely a real observation-based inversion will work for the western region for tracers that are mainly contributed by anthropogenic sources with regional fluxes that have similar temporal and spatial characteristics to fossil fuel CO_2 [e.g. wintertime CH_4 in Canada]. However, improvements are needed with the current inversion setup before real inversion is performed for the eastern region.

(2) What is the average footprint (emission sensitivity) coverage? This paper did not show.

Authors' response:

We will include this figure in the final paper (see companion figure 1).

The inversion domain should be largely determined by the footprint coverage, while the authors seem to choose the domain according to census.

Authors' response:

The inversion domain is based on the provincial boundaries that we will eventually compare our anthropogenic CH_4 flux estimates to the inventory which is only available at the provincial level. As shown in the new mean footprint figure, the inversion domains seem to be reasonable.

Does footprint of the three stations in ON province covers ON well? EGB and DOW stations are so close. Why not locate one of them in another place in ON?

Authors' response:

All stations chosen in this study were exactly the same as the existing site locations for these three provinces, AB, SK and ON. The FLEXPART footprints do provide good coverage of the anthropogenic CH4 and CO2 emission area in ON (in comparison to EDGAR emission data for example). The plan is to first conduct these synthetic observation experiments prior to real observation-based inversions. Therefore, this paper helps identify the problems and the sensitivity of the fluxes to the inversion setup.

How about the uncertainty reduction for the emissions in each sub-region after inversion?

Authors' response:

We prefer not showing any "uncertainty reduction" since we have demonstrated in the paper that the "uncertainty" does not cover the target. This suggests that the uncertainty ranges or values are not reliable for further interpreta-

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tions. This will be noted in the manuscript revision.

(3) The synthetic observation at each station simulated by the CarbonTracker model is the average value in the whole grid cell (1 deg by 1 deg). However, the Prior and Posterior modeled value by the FLEXPART is the concentration value at the exact location of the obs station. So, there is a representation error between the synthetic obs and modeled obs, which would lead to bias in interpreting the inversion results.

Authors' response:

The meteorological fields used to drive FLEXPART were at 0.2 deg by 0.2 deg that technically would not necessarily represent point measurements. The mismatch of model resolutions is reduced by using model results representative of afternoon condition with typically well mixed PBL and slowly varying concentration to capture some of the vertical and horizontal mixing in the atmosphere (thereby minimizing the resolution mismatch of the models, note that we do see much large differences comparing model nighttime data).

Using prior fluxes different from the target fluxes, we show in the modelled time series (Fig 3a and 3b) and the regression plots (Fig 6a and 6b) that the correlations of stations between FLEXPART and CarbonTracker can be quite high (R^2**>0.7) before inversion except for the DOW station (**R^2**>0.4). Although fluxes and transports are different, the prior concentrations and pseudo-observations are very close which indicate that "representation error" is really not a major concern. On the day to day synoptic time scale, no major differences can be found using 1x1 versus 0.2x0.2 for stations that are not surrounded by high emission sources. But it is certainly true in reality that this "representation error" will**

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become part of the total transport model error.

(4) The CO_2 concentrations at all four sites in SK/AB were almost identical to the background concentrations in spring and summer (Figure 3). It means the pollution signals were weak, which could lead to weak constraint on estimating the monthly and annually emissions in SK/AB. In the Table 2, CT2010 inventory (used a priori) is larger by 20% than the CT2011 (used as target) for SK/AB. In Figure 4, the "Annual Error" (relative percentage difference of the posterior estimates from the target flux) is also 20% by both MCMC and CFM methods. It seems suggest that the inversion has not done substantial adjustments of emissions.

Authors' response:

Figure 5b actually shows weak signals do not lead to weak constraint as long as the transport is good. The errors in the summer months are smaller than those in the winter. In the prior flux error only case shown as blue squares in Figure 4, improvement can be obtained using MCMC ($\approx$7% for AB/SK and $\approx$3% for ON). This represents large reduction in error in comparison to the prior flux errors of $\approx$25% for AB/SK and $\approx$12% for ON. However, it is not straightforward to determine how much error can be reduced using CFM because the inherent positive bias in the inversion method itself. As noted in the paper, the estimation errors increase as the number of sub-regions increases using CFM.

(5) When the number of sub-regions increased, the sub-region domain became smaller. Some sub-regions cover one, two or three grid cells (0.2*0.2). There are

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some approximation and errors when converting from the footprint value in grid cell to sub-regions. Does this issue contribute the large variety of inversion results with various numbers of sub-regions and negative posteriori values in some sub-regions close to the stations?

Authors' response:

The negative unrealistic values are mainly caused by transport and the instability of the inversion that seeks to solve for many spatially dependent sub-regions. The inversion results are well behaved for the 'no transport error case'.

(6) P22728, L15- P2279, L2: Does the simplification treatment of $(\sigma_{\mathrm{e}})^2$ and $(\sigma_{prior})^2$ affect significantly the posterior emissions? In this study, the prior errors were assigned constant for all sub-regions, which would lead to large prior error for small emission in one sub-region and small prior error for large emission in other sub-region. In this sense, emission values in some sub-regions could be changed easily by the inversion while some would be not.

Authors' response:

The prior errors are given in %, thus smaller emission regions have small prior uncertainties in absolute terms. We certainly have not examined all aspects/components in our inversion system. We plan to evaluate the impacts of different structures of the prior flux error variance-covariance and prior model-

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observation mismatch matrices in the cost function method in our future study.

Specific comments: P22721, L17: What is value for "majority"?

Authors' response:

It is about 70-80% in Canada according to the inventory report. We will add this to the revision.

P22722, L1: How did the authors do that "the gridded fluxes were aggregated into subregions to be optimized as shown in Fig. 2"? Some gridded fluxes cross over more than one sub-region.

Authors' response:

As noted in P22722, L11, the gridded fluxes were aggregated for visualization only in Fig.2. We will remove the words "to be optimized" to avoid confusion. All the sub-regions are specified with no overlapping grid points.

P22723, L4: why "5 day" was used as transport history? CO_2 is long-lived species. Is a longer backward simulation better?

Authors' response:

We are only concerned with the synoptic contributions for inversions and

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the longer temporal variability is extracted from the global model of CarbonTracker.

P22724, L19-20 and rest text: why the year 2009 was used for simulation in this study? The paper used CT2011 as the target year.

Authors' response:

We could have used any year prior to 2011, mainly because we have extensively used the CT modelled results and FLEXPART simulations for year 2009 for model comparisons and evaluations.

P22731, P7-11: The explanation seems be not robust. Many factors could contribute to the mismatch. Does the land sink contribute to the mismatch? Or "representation error" I mentioned above? Or the different resolutions in two simulations (1 vs. 0.2)?

Authors' response:

As pointed out earlier, we only used fossil fuel CO_2 for the prior flux and the target flux. There are no land sink or biospheric flux contributions. The representation error is negligible if not non-existence on the daytime (21UTC) synoptic time scale as explained earlier. The (fixed) difference in resolution is not likely to cause mismatch that varies with seasons. Therefore, the differences are due to the 2 different transports (CarbonTracker vs. FLEXPART), which is

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variable in time, is more likely to cause any mismatch.

P22738, L1 and in main text: why not show the “not shown”?

Authors’ response:

We could certainly show all the results, but because of the large amount of plots that we would have to include in the paper. We decided to only show the plots that were expected to be similar to the conditions in reality in which flux and transport model errors could co-exist.

P22738, L20-23: what is the Logic behind this claim?

Authors’ response:

Thank you for pointing out the confusion. We are only referring to Fig. 4b in the results for ON. We have modified the sentence from:

As shown in Fig. 4a and b (black squares), the lack of dependence on the number of sub-regions and the similarity of the non-linear pattern compared to set (III) confirm the fact that the estimation bias are introduced and dominated by the transport model error.

to:

As shown in Fig. 4b (black squares), the large variability with the number

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of sub-regions and the similarity of the non-linear pattern compared to set (III) indicate that the estimation bias are introduced and dominated by the transport model error.

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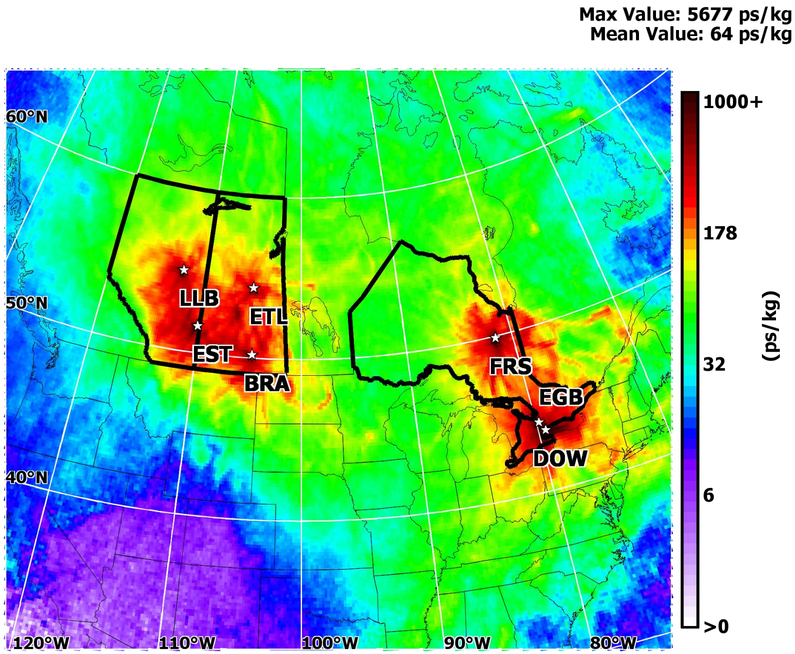

Fig. 1. Mean footprint emission sensitivity in picoseconds per kilogram obtained from FLEXPART 5-day backward simulations (21 UTC daily) averaged over all footprints of 7 stations and for January through December 2009. Measurement stations are marked with white stars. The western (AB/SK) and eastern (ON) inversion domains are in thick black boundaries.

Fig. 1.

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