# Response to interactive comment by Anonymous Referee 2 on "Estimates of CO2 fluxes over the City of Cape Town, South Africa, through Bayesian inverse modelling" by Alecia Nickless et al.

Alecia Nickless, Peter J. Rayner, Francois Engelbrecht, Ernst-Günther Brunke, Birgit Erni, and Robert J. Scholes

We would to thank the referee for their consideration of the paper and for their support of this work.

Referee 2 states: "*Overall I think this work makes an important contribution and should therefore be of interest for readers of ACP. Atmospheric inversions over cities are challenging and I appreciate the amount of work that has gone into this study. However, I think the manuscript can still be improved. The results section for example contains (too) many details including figures and tables. This makes it really difficult for the reader to focus on the main findings. Sentences are sometimes overly long and therefore hard to understand. Figure quality could also be improved.*"

The manuscript has been largely rewritten to improve the focus of the paper and improve clarity. Figures have been improved to be clearer, use better colour schemes, and to provide more information through legends rather than overly long and complicated captions. Certain sections have been removed or merged. For example, the supplementary section on the validation of the wind product from CCAM has been removed as the sites were generally not equipped or suited for this purpose. Instead more information on the general wind patterns within the domain has been provided, which is of more use in this context. The section 3.2.3 and 3.2.4 have been merged.

The referee makes the following specific comments:

"*Abstract:*

*- please consider rephrasing the sentence stretching from L6 to L11 on P1.*"

This has been re-written.

Previous: "Prior estimates of the fossil fuel emissions were obtained from an inventory analysis specifically carried out for this inversion exercise, making use of vehicle count data, population census data, fuel usage at industrial point sources, and aviation and shipping vessel counts. The inversion solved for the actual concentration measurements at each site, which was made possible by the use of the Cape Point background site to provide information on the boundaries, and was necessary due to the effect of topography on the atmospheric transport, affecting particularly the sensitivity of the Robben Island site to the surface fluxes."

Revised: "Estimates for the prior fossil fuel fluxes were obtained through a bespoke inventory analysis carried out specifically for this inversion study. This inventory analysis made use of a traffic model producing vehicle kilometres travelled on each stretch of road, population census data, fuel usage at industrial point sources, and aviation and shipping vessel counts. The inversion solves for the working week and weekend fossil fuel fluxes, the weekly net ecosystem exchange, and the average

weekly concentrations at the domain boundaries through modelling the concentrations of $CO_2$ at the Robben Island and Hangklip measurement sites."

"- *information such as "interquartile range" should be removed from the abstract (P1: L15, L16, L17, L18)*"

This has been removed from the abstract.

"*Main text:*

*P5, L9: "CABLE was dynamically coupled to CCAM" I don't know how many times I read this phrase in the manuscript. Please avoid repetitions.*"

As in response to the remarks by Referee 1, these sorts of redundancies have been removed through a thorough revision of the manuscript.

"*P6, L19: surface source grid "point" ?*"

What was meant here was "surface pixel"

"*P10, L5-L23: you talk about the generation of sensitivity matrix H, but you also mention sensitivity matrix T, which is confusing*"

This was a typo. It has been corrected in the revised manuscript. There is no matrix T.

"*P11, L14-L16: I don't understand this sentence. Please rephrase using shorter sentences.*"

This paragraph has been rewritten:

Previous: "Since the surface sources are expressed as fluxes of carbon, the contribution to the concentration at the measurement site is expressed in the amount of carbon seen at the measurement site from a particular source. In the case of the boundary sources (or contributions from outside of the domain) which are given as concentrations, their contributions to the concentration at the measurement site are expressed as a proportion of their concentration, dependent on their influence at the receptor site. Ziehn et al. (2014) shows that by calculating the Jacobian which provides the sensitivities of observed concentrations to boundary concentrations, the boundary contribution can then be written as:"

Revised: "The fluxes from the surface pixels are expressed in $\mathrm{kg\ CO_2 m^{-2}\,week^{-1}}$ and are transformed through $\mathbf{H}$ into contributions to the concentration at the measurement site in units of $\mathrm{ppm}$. The inversion solves for the concentrations at the boundary of the domain. The sensitivity of each site to each of these boundary concentrations (North, East, South and West) is given as a proportion of the concentration at the boundary, so that the sum of the boundary sensitivities for any given hour add to one. Ziehn et al. (2014) shows that by calculating the Jacobian which provides the sensitivities of observed concentrations to boundary concentrations, the boundary contribution can then be written as:"

"*P11, L23: "For the network design ..." ? It is confusing that you refer to a network design here.*"

This has been removed.

"*Figs.3+4: This figures need improvement. Please label the sub-plots. The information is provided in the caption, but it would be much easier to have it in the figure directly. The used colour scheme is probably not that helpful either.*"

These plots have been revised to make better use of subplot titles and legends to reduce the amount of text in the captions, and the text has been made clearer. The colours have been slightly altered to improve clarity. The colour scheme was deliberately chosen so that 1.) positive, negative and zero fluxes would be distinct. 2.) And the "jagged" graduation in colours so that the very large fossil fuel fluxes at point sources could be distinct, but also the smaller fluxes, such as those for transport and residential sources. These are smaller, but more numerous than the point sources, and we wanted these to be distinguishable from each other as well.

"*Section 3.1: I found this section far too detailed. Maybe some of the content could be moved to the supplementary material?*"

We agree. This section has been moved to the supplementary material.

"*Fig6: Please provide a legend for symbols and colours within the figure.*"

Legends for the symbols and colours used in these plots has been provided, instead of including this information in the caption.

"*Fig7: Is there a reason why Oct12, Dec12, Jan13 are missing? I am not sure if the diurnal cycle for all months is required in the manuscript?*"

These are plots of the observed diurnal pattern in the concentrations. Unfortunately observations were not available for all months. The monthly plots have been moved to the supplementary material, and instead the average diurnal plot over all periods has been improved in the manuscript (Figure 8 in the original manuscript).

"*Table 2: Consider to move this table to supplementary material.*"

Agreed. This will be moved together with Section 3.1. to the supplementary material.

"*P34, L8-L9: NEE or NEP?*"

The net primary productivity was used as the uncertainty in the net ecosystem exchange. This has been corrected in the manuscript. Generally, for most parts of South Africa, the NEE flux itself is very small, but could be resulting for relatively large respiration and photosynthesis fluxes. If the uncertainty in the NEE estimate was based on the NEE value itself, it would be unrealistically small. This discussion has been made clearer in the revised manuscript.

"*Figs. 9+10: Please provide a legend for symbols and colours within the figure.*"

These figures have been changed altogether to ensure that the time series is not squashed, and to separate out the day and night concentrations and residuals. Better use has been made of legends. Please see response to Referee 1 for an example of the new time series plots.

"*Fig.12: Please label the sub-plots (i.e. north, east, south, west)*"

Thank you. This has been done.

"*P42, L1-L3: Please rephrase this sentence.*"

This sentence has been revised.

Previous: "The innovation of the inversion can be observed through the differences between the prior and posterior flux estimates, which we refer to as the innovations, and through the change in the uncertainty estimates."

Revised: "We refer to the difference between the prior and posterior flux estimates as the innovations. The impact of the inversion on the flux estimates can be assessed through the size and direction of these innovations and through the reduction in the uncertainty estimates."

"*Figs.13+14: Add labels and improve colour scheme.*"

These plots have been improved. As discussed earlier, the colour scheme was selected to ensure that positive, negative and zero fluxes were distinct. The jagged colour graduation was also selected so that large fluxes could be displayed together with small fluxes, while still showing subtle differences between the smaller fluxes.

"*Table 3: Is this level of detail really required in the manuscript?*"

The purpose of including this table was so that the impact of the inversion could be assessed from month to month. This table attempts to summarise the distribution of the fluxes over the domain, and show how that distribution is changed by the inversion. This section has been largely rewritten. The table has been converted into a time series of box plots to show the distribution of these pixel-level fluxes.

"*P49: I have difficulties understanding the whole section on this page.*"

This section has been largely rewritten. The main point that this section makes is that, under the current inversion framework, the posterior off-diagonal covariances are very small. This is because the uncertainties in the modelled concentrations that are attributed to the flux contributions ($\mathbf{HC_{s_0}H}^T$) are small relative to the uncertainties specified in the observation error covariance matrix ($\mathbf{C_c}$). If the diagonal elements in $\mathbf{C_c}$ could be made smaller, then the posterior covariances would be much larger in magnitude. When we wish to estimate the difference between the fossil fuel and NEE fluxes $s_{f,i} - s_{NEE,i}$, in other words, to distinguish between the fossil fuel and NEE fluxes in the same pixel, the variance of this estimate is determined by the sum of the variances of these two fluxes plus twice the covariance between them: $C_{s(f,i;f,i)} + C_{s(NEE,i;NEE,i)} - 2 \times C_{s(f,i;NEE,i)}$ where $C_{s(f,i;NEE,i)}$ will be negative. If the posterior covariances were larger in magnitude (resulting in large negative correlations), then the inversion would be less able to distinguish between these two fluxes. At the moment the dominant term is the large uncertainty prescribed to the NEE estimates. Therefore, even though the negative correlations are small, the posterior variance of $s_{f,i} - s_{NEE,i}$ is still large, therefore the inversion does not distinguish well between NEE and fossil fuel fluxes under the current configuration.

But when we aggregate the fluxes from the same pixel, the variance of NEE plus the fossil fuel flux from the cell would be $C_{s(f,i;f,i)} + C_{s(NEE,i;NEE,i)} + 2 \times C_{s(f,i;NEE,i)}$ where $C_{s(f,i;NEE,i)}$ will be negative. The inversion always results in reductions in the uncertainty of the individual fluxes (or at worst they remain the same). If posterior covariances between the flux uncertainties were larger, which would occur if the uncertainties prescribed to the prior fossil fuel and NEE fluxes were smaller or if the elements of the observation error covariance matrix were smaller, then there would be a much smaller uncertainty in the aggregated flux estimates. The negative posterior covariances which are produced by the inversion mean that the uncertainty of the aggregated flux is always smaller than the sum of the uncertainty of the individual components. But by how much smaller depends on the prior uncertainties and the skill of the atmospheric transport model.

"*Figs. 15+16: I cant see the value of those figures. I don't think they are even referenced in the text?*"

Only Figure 15 is retained. It was an oversight that these were not originally reference, and this has been corrected. The discussion has been expanded as explained above. See also the response to Referee 1 on their comment marked B.

"*Section 3.2.3: Can you please check the units? You refer to fluxes, but units are in ktCO2.*"

The units are $\mathrm{kt\ CO_2\ week^{-1}}$ emitted from the domain of the inversion. This has been clarified.

"*Fig. 17: Please add a colour legend. Check units.*"

This has been clarified and legend added.

"*Section 3.2.4: Units not consistent. I think, they are all fluxes.*"

This section has been merged with section 3.2.3 which now considers the aggregated fluxes. The units have be made clear to reflect that for those fluxes referred to in the original section 3.2.4, the units are $\mathrm{kt\ CO_2\ month^{-1}}$.

"*Table 5: move to supplementary material?*"

This whole section has been moved to the supplementary material.

## References

Ziehn, T., Nickless, A., Rayner, P. J., Law, R. M., Roff, G., and Fraser, P.: Greenhouse gas network design using backward Lagrangian particle dispersion modelling – Part 1: Methodology and Australian test case, Atmos. Phys. Chem., 14, 9363–9378, doi: 10.5194/acp-14-9363-2014, 2014.