

## ***Interactive comment on “Carbon Monitoring Satellite (CarbonSat): assessment of scattering related atmospheric CO<sub>2</sub> and CH<sub>4</sub> retrieval errors and first results on implications for inferring city CO<sub>2</sub> emissions” by M. Buchwitz et al.***

**M. Buchwitz et al.**

michael.buchwitz@iup.physik.uni-bremen.de

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First of all, we would like to thank "Anonymous Referee #2" for the careful review and for providing useful interactive comments on our manuscript "Carbon Monitoring Satellite (CarbonSat): assessment of scattering related atmospheric CO<sub>2</sub> and CH<sub>4</sub> retrieval errors and first results on implications for inferring city CO<sub>2</sub> emissions" by M. Buchwitz et al. All comments will be carefully considered for the revised version of the manuscript. Below we give point by point answers to each of the referee's comments.

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1. Referee: "Split the manuscript into two. Provide more information by text."

Both referees recommend to significantly shorten the manuscript, e.g., by removing parts (e.g., referee #1 suggests to remove the part on plant fluorescence) or by splitting the paper in two or more separate paper (e.g., referee #2 recommends to publish the part on the Berlin CO<sub>2</sub> emissions in a separate paper). Both referees also ask for more explanations on various items. To consider these comments we plan the following for the revised version of the paper: As the paper is already quite long - and adding explanations will make it even longer - we will remove the Berlin emission part, which will be published in a separate paper.

2. Referee: "Need more work for Berlin emission OSSE"

Answer: The main purpose of the presented assessment was to quantify to what extent the Berlin CO<sub>2</sub> emission estimates are influenced by the random and systematic errors of the CarbonSat observations taking into account the spatio-temporal sampling of CarbonSat. Other errors, e.g., errors due to imperfect atmospheric transport modelling and imperfect knowledge of the spatial pattern of the anthropogenic emissions have not been quantified. These additional errors, which arise from error sources not directly related to CarbonSat, still need to be quantified. This is not trivial, as it requires assumptions on transport modelling errors and likely errors of the spatial (and temporal) pattern of the emissions. To consider this we will follow the advice to publish the results on the Berlin CO<sub>2</sub> emissions in a separate paper (see above). As a consequence, the entire Section 6 will be removed when generating the revised version of the manuscript.

3. Referee: Figures: "Text on figures should be readable. Text on figures are often too small to read (although I can read them if magnified). Also, some figures are small and busy. I think this is trivial to implement."

Answer: All figures will be checked and for those figures, which are busy and where the text is too small, this will be improved.

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Answers to referee's "Line by line comments":

Referee: P4771, L15: "BESD/C, spell out if appropriate."

Answer: Will be done.

Referee: P4784, L18: "Or prescribing aerosols using aerosol models?"

Answer: Good suggestion. This will be added as one of the possibilities to reduce aerosol related errors.

Referee: P4785, L27: "criterium -> criterion".

Answer: Thanks.

Referee: P4786, L1: "criterium -> criterion".

Answer: Thanks.

Referee: P4795, L22: "A reference for WRF?"

Answer: Not needed any more as entire section will be removed (see above).

Referee: P4795, L24: "A reference for VPRM?"

Answer: Not needed any more as entire section will be removed (see above).

Referee: P4795, L29: "Do you keep consistency in prior fluxes between the global simulation by TM3 and the regional high-resolution simulation? Especially, I am curious about fossil fuel emissions as you used IER (which is a regional dataset) for the European domain simulation. As you are solving for fossil fuel emissions, you can just choose a fossil fuel emission data as a good spatial proxy. Is that what you are assuming? Even if so, I still think that the consistency in prior flux is important (e.g. mass conservation in your whole system). The estimated fossil fuel emissions (in the regional domain) should be consistent with the emissions used in the global simulation."

Answer: Consistency between global and regional high-resolution simulations: The

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simulations are broadly consistent but not exactly identical, as TM3 uses EDGAR yearly fluxes whereas the high-resolution model uses IER hourly emissions. However, this is not considered a major problem for the purpose of this study as we focus on a small region and use a method which is insensitive to XCO<sub>2</sub> background variations. The far-field influences are therefore essentially negligible. What is important is that the small scale spatio-temporal XCO<sub>2</sub> pattern in and around Berlin are realistically modelled, in particular those pattern arising from anthropogenic emissions in and around Berlin as well as biogenic emissions. Fluxes originating from sources and sinks located far away from the target region will typically result in quite smooth modifications of the background XCO<sub>2</sub> values, which are of less relevance as (unknown) offsets are considered by the inversion method.

Referee: P4796, L3: "I would suggest to adding an equation to what you are solving in your inversion (define your cost function). That would be informative for the audience of AMT. It was tough to understand what you are doing here by the information provided."

Answer: Good suggestion. This will be done when generating the new paper on the Berlin CO<sub>2</sub> emissions (see above).

Referee: P4796, L4: "So you assume you can well reproduce anthropogenic XCO<sub>2</sub> patterns in your model. I cannot agree with this at this point. Here are several thoughts: 1) Yes, we are prescribing fossil fuel emissions in inversions. But that is a different inversion problem (often solving for natural sources and sinks). 2) Given IER dataset is constructed using (probably) the best available activity data, you might be able to well prescribe fossil fuel EMISSION patterns (I am here still ignoring temporal variations in emissions). But emission patters is not identical to XCO<sub>2</sub> pattern due to atmospheric transport (although your instantaneous XCO<sub>2</sub> image could put you in a better position to justify it). For instance, Pillai et al. (2010) suggested that most variability we see in XCO<sub>2</sub> could be explained by variability in the lower atmosphere. However the correlation was still 0.37 in the better case (I acknowledge that R=0.37 at that spatial scale is great!). So you can't assume like "Emission pattern = XCO<sub>2</sub> pattern". 3) To

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estimate emissions by fitting modelled XCO<sub>2</sub> fields to your planned XCO<sub>2</sub> (or XCH<sub>4</sub>) images that have a 2 x 2 km resolution, it seems to me that you need to have an amazing modelling capability. I imagine the errors would arise from the assumption of replicating XCO<sub>2</sub> patterns well, would be significant. To verify, you really need to implement simulations at the 2 x 2 km resolution. 3) Once again, to solely attribute the mismatch between XCO<sub>2</sub> images and modelled XCO<sub>2</sub> fields to the error due to geophysical difficulties, you would need to be perfect in your simulation. Do you use IER hourly temporal variations in emissions for this OSSE? Potential biases in XCO<sub>2</sub> modelling arising from wrong temporal variations could be significant for your CarbonSat case (There is a paper by Nassar et al. (2012) simulated hourly XCO<sub>2</sub> fields)."

Answer: We do not assume "Emission pattern = XCO<sub>2</sub> pattern". However, we assume that the (additive) part of the XCO<sub>2</sub> pattern caused by the (anthropogenic) emission pattern can be modelled well enough. We agree that there will be an additional error due to errors of the transport modelling. This error has not been quantified as we focus on CarbonSat related errors. However, we agree that also other errors need to be quantified. Yes, we use hourly IER emissions and yes, we agree that also errors due to assumptions on the time dependence of the emissions need to be quantified (CarbonSat will be able - at least to some extent - to provide information on the time dependence of the emissions for a time period of several hours before the overpass (depending on wind speed) but also this needs to be studied in detail and quantified). We agree that it would be better to perform the simulations at 2 km x 2 km but we don't think that this will significantly change the conclusions in terms of number of good overpasses and related estimates of the random and systematic errors of the Berlin CO<sub>2</sub> emissions.

Referee: P4796, L11: "A reference for STILT? (e.g. Lin et al., 2003)"

Answer: Not needed any more as entire section will be removed (see above).

Referee: P4796, L20: "I assume 54 MtCO<sub>2</sub>/yr is annual total emission for the region

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aimed. Then did you account for seasonality (or weekly variations) in emissions here in this OSSE?"

Answer: No, the reported emissions are the emissions at the time of day of the overpass as we use hourly emissions (see above).

Referee: P4797, L3: "We could simulate anthropogenic XCO<sub>2</sub> contributions in a model. But in practice, we can't tell how well the contributions are replicated given the presence of biogenic sources (as well as errors associated with high-resolution modelling). Could you comment on this? If you verify your method at a site where you could really disentangle anthropogenic and biogenic contributions (e.g. Vogel et al., 2013), it would be convincing."

Answer: To deal with the issue of XCO<sub>2</sub> variations due to biogenic sources and sinks we have reported errors for the two relevant cases including the one where we treat the biogenic XCO<sub>2</sub> variations as a systematic perturbation of the XCO<sub>2</sub> which cannot be modelled at all. This is the worst case situation and the corresponding errors are reported in our paper. As shown, the systematic CO<sub>2</sub> emission errors are larger but not overwhelmingly large. The main reason for this is that the Berlin emission plume typically generates a spatial XCO<sub>2</sub> pattern which looks much different than the spatial pattern due to biogenic emissions. So in most cases the two sources can be disentangled at least reasonably well. In our paper we aimed at answering the question how often and how well we can derive the emissions of Berlin. In this context it does not seem very helpful to study another region where one "could really disentangle anthropogenic and biogenic contributions" (whatever this means).

Referee: P4797, L10: "VPRM is calculating biogenic fluxes by considering instantaneous weather (which is simulated by WRF). Correct?"

Answer: Yes.

Referee: P4797, L14: "This could be definitely true in a theoretical world (no error!),

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but we don't know how the low correlation could help you to disentangle two emission contributions. Any reference or supporting information for this?"

Answer: We are not sure if we fully understand this question. Low correlation means that the spatial patterns are different and this is the underlying reason why the two sources can be separated.

Referee: P4797, L23: "It seems to me this is a big assumption. Similar to biosphere (not exactly the same although), human activities could also be a function of weather (e.g. heating/cooling). We could use "climatology" of emission temporal variations, however the assumption could introduce a significant error especially if you implement simulations at a high resolution. Any consideration for this in your OSSE? Also, modelling PBL should not be trivial at the spatial scale of interest. You need to do a good job to simulate the formation of PBL to get an accurate CO<sub>2</sub> mixing ratio close to the surface (which CarbonSat has its sensitivity). Maybe you could comment on this from a work by Kretschmer et al. (2012)?"

Answer: As already explained above we agree that the additional error due to the time dependence of the emissions needs to be quantified.

Referee: P4798, L10: "What if you create a figure of total XCO<sub>2</sub> (anthropogenic plus biosphere = Fig. 12a plus 12b)? Do you still see clear enhancement due to the anthropogenic emissions in the XCO<sub>2</sub> field?"

Answer: This depends on the situation. Sometimes yes, sometimes not. We will address this aspect when writing the new paper on the Berlin emission estimates.

Referee: P4798, L13: "I need your help to understand. I see biogenic XCO<sub>2</sub> variability even in the white box in Fig 12. The variability is about the same order of the magnitude as XCO<sub>2</sub> enhancements we see in Figure 12 (A). What is constant?"

Answer: The first row of Fig. 12 shows the biogenic XCO<sub>2</sub>. It varies everywhere including the target region (white box). The last row shows the anthropogenic XCO<sub>2</sub>. It

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also varies everywhere including the region outside of the target region. The variations of the anthropogenic XCO<sub>2</sub> are not due to biogenic CO<sub>2</sub> fluxes but only due to anthropogenic CO<sub>2</sub> emissions and atmospheric transport. Nothing is constant in the maps shown in Fig. 12. Our sentence with "essentially constant" is misleading. This will be improved when writing the new paper (see above).

Referee: P4798, L20: "Once again, I cannot agree with this assumption at this point."

Answer: See our answer already given above.

Referee: P4798, L25: "Yes, this is what I am worried about."

Answer: Therefore, this has been mentioned and the corresponding error quantified.

Referee: P4798, L27: "This sentence might be missing something."

Answer: We guess you refer to sentence: "In this case a systematic error of the retrieved CO<sub>2</sub> emission results". The sentence will be improved when writing the new paper (see above).

Referee: P4798, L28: "So the discussion here is based on the assumption that you can model anthropogenic XCO<sub>2</sub> very well. You need to show information that supports your assumption above. At least, the error coming from the assumption is small enough compared to the error coming from the satellite side."

Answer: See our answers on this topic given above.

Referee: P4799, L17: "much too -> too much (?)"

Answer: OK.

Referee: P4800, L1: "Once again, this seems to be a big assumption."

Answer: See our answers on this topic given above.

Referee: P4800, L5: "Yes, you can implement an inversion by adding one more scaling factor. Have you checked if it really works that way? (would you be able to really

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disentangle biogenic and anthropogenic contributions?)"

Answer: As already explained above we have quantified the error arising from biogenic XCO<sub>2</sub> contributions. This is all that is required for the purpose of this study. Again, it is unclear what you mean with "to really disentangle biogenic and anthropogenic contributions".

Referee: P4801, L9: "So how would you calculate the annual total emission for Berlin, given you would get 22 (or 39) XCO<sub>2</sub> snapshots and associated emissions estimates? Would it be possible to derive a policy-relevant number?"

Answer: The policy-relevant number will be primarily based on comparisons with emission inventories reporting time resolved (e.g., hourly) emissions such as IER. The sparse sampling in time will not permit to derive accurate annual emissions.

Referee: P4801, L16: "Yes, this is true in OSSE. But in practice, if we go higher resolution in space and time, we would have more error in modelling (No?)."

Answer: Probably this is correct for the modelling related aspects. This is however only one aspect. Overall, we think that high resolution will help to improve the situation, e.g., to better disentangle anthropogenic and biogenic emissions and possibly also to verify assumptions on the assumed spatial pattern of the emissions and for other reasons, e.g., more cloud free observations.

Referee: P4801, L18: "This is exactly what I want to say. This is very critical to conclude this OSSE study even you focus on systematic errors from satellite side. Without dealing this, I think it is tough to make a conclusion."

Answer: Therefore, we have added this sentence.

Referee: P4804, L13: "occure -> occur"

Answer: Thanks.

Referee: P4807, L5: "Given many assumptions and future works acknowledged by the

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authors, I like to have a statement saying like "the error could be much larger"."

Answer: We will consider this when writing the new paper (see above).

Referee: P4839, Fig.12: "Would it be possible to use the same color scale (especially for bio-genic and anthropogenic emissions) or create a figure showing biogenic XCO<sub>2</sub> fields plus anthropogenic XCO<sub>2</sub> fields? (which is you are going to fit in your inversion, if I correctly understood). "Modelled" or "Modeled"? Please keep consistency throughout the manuscript (probably, "modelled" for AMT?)."

Answer: We will consider this when writing the new paper (see above). We will improve the consistency for "modelled", thanks.

Many thanks also for the providing additional references.

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