Tracking city CO_2 emissions from space using a high resolution inverse modeling approach: A case study for Berlin, Germany

Authors' responses to reviewers' comments:

We would like to thank both referees for their careful reviewing and constructive comments, recommendations, and suggestions. Our responses to these comments are as follows:

[RC]: Reviewer's comment
[AR]: Authors' response
[ME]: Manuscript edits & modification

Reviewer #1

[RC] "One criticism is that the accuracy needs in terms of city emissions are not discussed. In the introduction, it is explained that an independent evaluation of the emissions is needed to verify the impact of mitigation efforts. If this is the primary objective of the mission, I would thing that an accuracy of a few percent is needed. The introduction also mentions the objective of inventory verification. However, the accuracy that is required for such objective is not mentioned. Finally, the introduction mentions the potential of independent measurements of CO2 for emission trading. However, I believe that emission trading is at the scale of industries, and not at the scale of the cities. I thus recommend a better description of the needs with a quantification of the accuracy requirement. Clearly, this question has a strong impact on the results. Indeed, the abstract conclude by saying that "CarbonSat is well suited to obtain city scale CO2 emissions". Since there was no requirement set, one cannot draw such conclusion. "

[AR] We agree that the paper can be improved in this respect and we will modify the Introduction and the Abstract to consider this comment. The text will be modified as follows:

> **[ME]** P2L13 in ACPD: "The reporting of the emissions of CO_2 is currently determined by national and regional agreements and legislation. This is an evolving topic for policy makers. For example, there exists an emission inventory which accounts for total annual U.S. emissions between 1990 and 2014 (EPA, 2016). In the European Union, the monitoring and reporting of greenhouse gas emissions are performed and regulated under the Commission Regulation (EU) No 601/2012 (European Commission, 2012). Similarly, the UK Government has announced, under the Companies Act 2006 (Strategic Report and Directors' Report) Regulations 2013, that companies are required to report their annual greenhouse gas emissions in their directors' report (see http://www.legislation.gov.uk/uksi/2013/1970/pdfs/uksi_20131970_en.pdf). There is also a guideline for national greenhouse inventories prepared by a task force of the IPCC (IPCC 2006). Following the agreement of the UNFCCC COP21 in Paris 2015, it is likely that new guidelines for reporting the emissions of greenhouse gases will be required.
>
> The uncertainties, i.e. the sum of systematic and stochastic error, in the national average of annual fossil fuel CO_2 emissions from the United states is estimated to be 2 to 5 % (EPA, 2016). The corresponding values for countries without well-developed energy sector statistics are even higher, giving rise to uncertainties of about 10 to 20 % at the national level (Gregg et al., 2008). When disaggregating these national emissions at fine scales (e.g. city scale) based

on conventional accounting methods, the associated uncertainties are expected to be significantly higher compared to those of national averages (Oda and Maksyutov, 2011). Hence reliable emission estimates are not often available at a scale relevant for urban emissions and the associated uncertainties. "

P2L20 in ACPD: "In order to assess accurately the contribution of a city or other emission hot spot to the CO_2 or other GHG emission, accurate knowledge of the surface fluxes at high spatial and temporal resolutions are needed. Ideally the accuracy of the estimated flux needs to be high for unambiguous attribution of source strength. The uncertainty of these estimations is required to be reduced to the extent that is feasible. In ESA (2015) it is noted (see their Sect. 4.1.2) that accuracies better than 10% would be useful for providing important additional information for cities where inventories exist, and accuracies better than 20% would contribute knowledge for cities where inventories do not exist."

"The results show that these potential space-based top-down flux estimates have high accuracy; hence this study contributes to the definition of achievable targets for emission fluxes at the city scale."

<u>Abstract</u>

P1L33 in ACPD: "Overall, we conclude that a satellite mission such as CarbonSat has high potential to obtain city-scale CO_2 emissions as needed to enhance our current understanding of anthropogenic carbon fluxes, and that CarbonSat-like satellites should be an important component of a future global carbon emission monitoring system."

[RC] I have been confused with the size of the state vector λ. On the one hand, I understood (p7, line 20 and below) that only the scaling to prior emissions of the Berlin region was retrieved (the spatial and temporal variations of the emissions are assumed) so that there is a single element in the state vector. On the other hand, on page 8 (around 5), it is stated that the prior uncertainty is a matrix with no correlation, which clearly indicates that there are several elements in the state vector. Please clarify.

[AR] The text will be modified to clarify this.

[ME] P7L21 in ACPD: "The other element is a constant, i.e. $\boldsymbol{\lambda}_0 = 0$, for the entire scene per overpass to account for variations of the background XCO_2 (see Eq. 4) and to treat the background variations independently of the city emissions as done in Buchwitz et al. (2013b)."

[RC] Page 9 around line 30. I could not understand why a 500 km swath instrument leas to 25 valid observations during the year while the same with a swath width of 240 km leads to much more than half of this number. I would have expected that, as the swath is reduced by a factor of slightly more than 2, the number of valid observation be reduced by a factor of significantly more than 2. Please discuss. Is this number typical of what can expect for cities with similar cloud cover as Berlin, or is the CarbonSat orbit centered over Berlin which makes it a favourable case ?

[AR] It is mentioned in Page 7 line 16 in ACPD that there are 41 days of potential overpasses over Berlin for the 500 km swath width, based on the quality filtering scheme as described in Buchwitz et al. (2013a). However, as stated in page 9 line 27 in ACPD, we have applied an additional quality filter based on the posteriori random error of the retrieved emission, i.e., results are not shown for the days where retrieved emission random error exceeds 25%. This resulted in the number of valid days reducing to 25 for the 500 km swath width. The additional quality filter did not reduce much the valid observations for the 240 km swath width. The text will be modified as follows:

> **[ME]** P9L30 in ACPD: "Applying this additional quality criterion has further reduced the number of potential overpasses for the 500 km swath width. "

[AR] This number ("N") is something typical we would expect for cities with similar cloud and SZA.

> **[ME]** P9L31 in ACPD "The value obtained here for "N" useful overpasses is expected to be typical for other cities with similar cloud coverage and latitude."

[RC] "A quite high scaling factor" (between CO2 and aerosol optical depth). Please explain the reasoning to state that it is a high scaling factor. Indeed, eventualy a CarbonSat-like mission may be used to monitor cities that are not as "clean" as Berlin. For such cities, the scaling factor chosen may be an underestimate.

Will be modified in the text as follows:

> **[ME]** P9L34 in ACPD "To quantify the urban aerosol enhancement over a region around two power plants in Germany and to study their impact on emission estimates, Krings et al. (2011) followed the above criteria and used an AOD scaling factor of 0.05 per 1% (4 ppm) of local ΔXCO_2. As compared to their study, we have used a much higher scaling factor of 0.2, i.e., the AOD change, ΔAOD at 550 nm is 0.2 per 4 ppm of local anthropogenic ΔXCO_2."

[RC] I was surprised by the discussion of the "clean pixel method". In the present state, it is very hard to understand and it comes at od with the rest of the paper. I strongly suggest to remove this section.

[AR] The discussion about the clear-pixel method has been removed.

[RC] 14C is mentioned. I do not think that anyone believe that 14C can be measured from space. The present paper is about spaceborne observation and I think it is misleading to mention 14C here. As for the other tracers (CO, NOx), the authors do know that, when adding this source of information, one also adds an unknown variable (relative fraction of emissions). Thus, I think it is misleading to suggest that the concomitant measurement of these gases would allow a distinction of the biogenic and anthropogenic contributions.

[AR] The mention of $\delta^{14}C$ has been removed as it cannot be measured from space with available technology. However, we disagree with the following statement about the additional tracers. There are a number of studies (including satellite-based) which showed the potential of using multiple species as tracers for anthropogenic CO_2 emissions from fossil fuel combustion. We see the importance of potential synergies to utilize these measurements to separate the anthropogenic and biospheric parts of the signals. The text will be modified to include the citations of these previous studies.

> **[ME]** P13L5 in ACPD "To assess the relative contribution of biogenic and anthropogenic sources, one can utilize additional co-emitted tracers such as CO and NO_X (Newman et al. 2013; Silva et al., 2013; Berezin et al., 2013 and Reuter et al. 2014). In the time frame of a

potential CarbonSat mission, Sentinel-5 will be providing data on CO and tropospheric NO_2 (Ingmann et al., 2012), which when combined with CarbonSat data is expected to provide information for the attribution of air masses originating from fossil fuel combustion. Depending on the extent of the variability and the possible uncertainties, we can also rely on the biospheric and global model simulations to differentiate different source-sink contributions."

[RC] I could not understand the argument in the sentence "By showing that the systemic error of the retrieved fluxes. . .". Please rephrase

[AR] done

[ME] P15L22 in ACPD "By showing that the systemic error of the retrieved fluxes is lower than the difference between the prior fluxes and the true fluxes in most cases, the results from the inversion experiment build confidence in our uncertainty estimations and ensure that the optimization is done correctly."

[RC] Finally, I have a recommendation for discussion: The simulations are made at 10 km resolution and the authors do not mention a significant loss of information from the original 2 km of the CarbonSat instrument. One should then wonder what is the added value of the high spatial resolution of CarbonSat. It seems that 10 km resolution is good enough to observe the plume from the Berlin city

[AR] The point is already discussed in the manuscript. Please see page 8, line 28 and page 9, line 14 in ACPD. However, in order to make this point into the Discussion Sect., we modified the manuscript as follows:

[ME] P13L43 in ACPD "When using observations at CarbonSat's 2 km spatial resolution, as mentioned in Sec. 4.1, it is likely that the magnitude and variability of local anthropogenic XCO_2 enhancement would be higher than our estimation that is based on simulations at 10 km spatial resolution. One of the main advantages of CarbonSat's resolution is its ability to provide a large number of cloud-free observations, and this study identified the potential observations over Berlin by utilizing CarbonSat's 2 km spatial resolution. "

[RC] Figure 2 is mentioned but not discussed. It does not bring anything to the paper and I thus strongly suggest to remove it.

[AR] done

[RC] In Figure 3, it seems that the original data (10 km resolution) went through spatial smoothing. I would like to see the pixels. Also, a zoom over the Berlin region would be appropriate

[AR] done

[RC] Figure 4 : Please use Y axis that start at zero. The current presentation is somewhat misleading. The difference between IER and EDGAR are surprisingly large. I wonder whether there are arguments to favor one versus the other.

[AR] The y-axis range has been modified. Our analysis shows large difference in emission intensities between IER and EDGAR over Berlin; however, it is difficult to say which one is more appropriate than the other. We will add following line in revised version of the manuscript:

> **[ME]** P5L15 in ACPD "However, based on available sources of information it is difficult to conclude which inventory is more accurate."

[RC] Figure 6: There are features I do not understand: Around day 75, two successive prior emission values show differences by a factor of two. Based on Figure 4, I cannot understand how the weekly, seasonal or daily cycles can explain a difference by a factor of two (assuming the observation is around 11 when there are little hourly variations). Please investigate

[AR] Fig. 4 in ACPD (will be Fig. 3 in the revised version of the manuscript) shows a one-year average of weekly, seasonal and diurnal cycles, i.e. 366 * 24 = 8784 data points have been used for this averaging. On the other hand, Fig. 6 in ACPD (will be Fig. 5 in the revised version of the manuscript) shows individual points corresponding to "N" good overpasses (used for inversion) and these individual peaks are smoothed out in Fig. 4 in ACPD. The plot showing almost the full time series is shown below and illustrates this further.

In addition to this, some more details will be given in the revised manuscript as follows:

[ME] P9L4 in ACPD: "Note that those fluxes "seen" by CarbonSat can vary significantly from one overpass to the next, as the temporal variations show a strong diurnal cycle (see also Fig. 3), and the time elapsed to transport the plume to where it is observed by CarbonSat changes with wind speed."

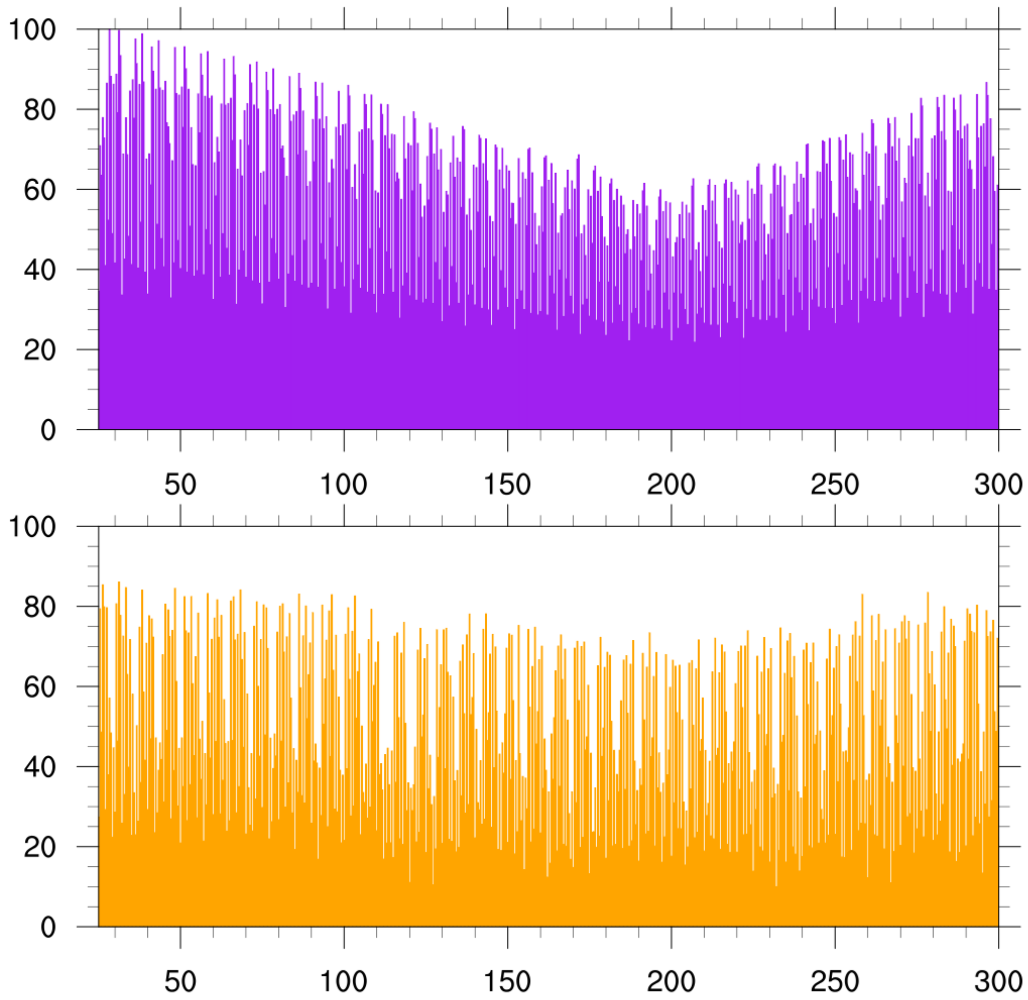

Figure 1: Anthropogenic flux over the target region based on (top panel) the EDGAR inventory, and (bottom panel) the IER inventory. The x-axis represents days of the year in 2008. Note that data are shown for the days from 25 to 300 to be consistent with Fig.6 in ACPD and to ease the visual analysis. The y-axis represents the total emission fluxes in $MtCO_2$/year

Reviewer #2

[RC] P3 L10: "The goal swath width is 500 km, but a smaller swath width will likely be implemented to limit cost (ESA, 2015). " Here and elsewhere in the text, check the consistency with the fact that CarbonSat was not selected.

[AR] Done. Will be modified as follows.

> **[ME]** P3L10 in ACPD: "The goal swath width for the proposed CarbonSat mission was 500 km, but smaller swath widths were also considered to limit cost (ESA, 2015)."

[RC] P3 L17: "...Buchwitz et al. (2013a)... " I could not find Buchwitz et al. (2013b) in references (which is also cited further in the manuscript). I supposed you mean the paper: "Carbon Monitoring Satellite (CarbonSat): assessment of scattering related atmospheric CO2 and CH4 retrieval errors and first results on implications for inferring city CO2 emissions" Buchwitz et al. AMTD, 2013 Please, confirm.

[AR] Thank you pointing this out. Buchwitz et al. (2013a) is the AMT paper and Buchwitz et al. (2013b) is the one which is given above. The reference section has been corrected accordingly.

[RC] P4 L10: "41 vertical levels" Please, indicate the model top at hPa

[AR] Done. Will be modified as follows.

> **[ME]** P4L10 in ACPD: "and the model top is 1.0 hPa"

[RC] P4 L26: "An overview of the flux optimization is shown in Fig. 2." I think the reference to Pillai et. al. 2012 is enough. As well as for P11 L19-20, "As can be seen in Fig. 2". I suggest to remove Fig. 2

[AR] Done.

[RC] P5 L11: "Figure 4 shows..." I suggest to keep consistency between figures and use a) b) c) etc. for different panels throughout the paper.

[AR] Done.

[RC] As remark, I suggest to add more clarifications in sections 2.2 and 3.2. At this shape it's hard to get into details of the inversion system. It would be useful to add dimensions for every component of the system…..

[AR] Done. Will be modified as follows.

> **[ME]** P7L26 in ACPD: "… and the dimension of K is $n \times m$ where n corresponds to the numbers of elements in the state vector and m is the number of XCO_2 observations."

[RC] P6 L16: "Eq. (4)" -> "Eq. (6)"

[AR] Done. Thank you.

[RC] P8 L8: "Any error correlations are neglected, hence Sprior is set to be a diagonal matrix" - is the measurement error covariance matrix also diagonal? If so, add few words about this assumption, especially for CarbonSat-like XCO2 observations.

[AR] Will be modified. Please see our response to Referee #1

[RC] P10 L6: "...typically differs... " - Typically for Berlin region or in general?

[AR] in general

[RC] P10 L16-17: "In general, we find that the two different swath widths have a negligible impact on the daily SE of the retrieved emissions" - Please, rephrase this sentence as in conclusion section.

[AR] Will be modified as follows:

[ME] P10L17 in ACPD: "…although decreasing the swath width reduces the "N" useful overpasses."

[RC] P12 L25-26: "Furthermore, the systematic errors of the retrieved emission fluxes for both swath widths are found to be lower than the systematic error of the prior fluxes (estimated based on "true" fluxes) except for a very few cases,..." Please, rephrase this sentence.

[AR] Will be modified as follows:

[ME] P12L25 in ACPD: "… swath widths are found to be lower than the difference between the prior fluxes and the "true" fluxes except for a very few cases…"

[RC] P12 L12: "...in the target region is notably different." - Here need to add ref. to the figure 6 in the end of the sentence. Otherwise this figure is not mentioned in the paper at all.

[AR] Will be modified as follows: (please note that Fig. 6 will be Fig.5 in the revised version of the manuscript)

[ME] P9L4 in ACPD: "Figure 5 shows an overview of prior fluxes used for these inversions."
P12L12 in ACPD: "notably different (see Fig. 5)."

[RC] P15 L22-23: "By showing that the systemic error of the retrieved fluxes is lower than that of the prior fluxes (estimated based on true fluxes) in most of the cases," – please, consider to rephrase this sentence

[AR] Will be modified. Please see our response to Referee #1.

[RC] Also, as a comment to section 4.3 I think there might be effect of ignoring transport model uncertainty giving less weight to the prior fluxes.

[AR] Yes, we do agree that there will be an impact of transport uncertainty, but the scope of this study is to estimate the retrieved flux uncertainties that are caused only by CarbonSat's related errors. This is already mentioned in the manuscript. Please see page 14, line 1 in ACPD.

As for section 5 - Discussion, I agree with Referee #1 about introduction and discussion of the "clean pixel method" here. From my point of view it disturbs the logic of the paper and I suggest to remove this paragraph.

[AR] Removed. Please see our response to Referee #1.