Authors’ Response to Reviews of

Methane retrieval from MethaneAIR using the CO2 Proxy Approach: A demonstration for the upcoming MethaneSAT mission

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RC: ***Reviewers’ Comment***, AR: Authors’ Response, ☐ Manuscript Text

1. General Comments

The authors have added references and clarified methodologies as requested and expanded sections in the supplement to address the feedback on detailing the mathematical bases and assumptions of their model, which I previously considered insufficient in some parts. They made significant updates where needed, while also justifying their original approaches when they disagreed with the comments.

Overall, their response improves the manuscript’s clarity and demonstrates a commitment to addressing the reviewer’s concerns. Therefore, the manuscript should be published after minor revisions are made.

2. Specific Comments

RC: ***Consider revising the order of the conclusions in Section 8 to present the most important aspects first, followed by the less critical ones. In my opinion the temperature-induced shifts, for instance, should not be the first aspect discussed in the conclusions.***

AR: As this is a style request, we respectively decline, as we prefer to list the conclusions in chronological order.

RC: ***Add clarification to distinguish between the terms "quantification" and "detection”, noting the term “quantification” is italicized at line 589 and that the detection limit of 121 kg/h and the quantification limit of 200 kg/h are considered consistent.***

AR: The term was italicized to emphasize that they are different metrics, as there was confusion in the preprint. I think the terms are self explanatory. Detection means that we can identify a source of methane, but the enhancement is too low for it to be quantified. Quantification means that it is large enough that it can be. Thus the detection limit should always be lower than the quantification limit.

RC: ***It would be beneficial to include a table comparing the specifications of MethaneAIR and MethaneSAT, as numerous figures are mentioned throughout the manuscript.***

AR: Addressed in specific comment Line 42.

RC: ***15: Please ensure that the number 2.5 ppb for the latitude gradient bias is clearly referenced in the main text, as it currently appears to be missing from Section 5.2.***

AR: The 2.5 ppb refers to the mean bias between the instruments. We have reworded the sentence to make this clearer

> MethaneAIR retrievals were also intercompared with those of TROPOMI; The mean bias between instruments is 2.5 ppb, and the latitudinal gradients for the two datasets are in good agreement.

RC: ***26: Consider to clarify what is meant by "fine spatial resolution" and "large swaths" in the context of MethaneAIR, and provide specific information similar to the details given for MethaneSAT in the following sentence.***

AR: We have clarifed the sentence by attaching numbers to the spatial resolution and mapping area, and included the approximate target size for MethaneSAT.

> The results showcase the capability of MethaneAIR to make highly accurate, precise measurements of methane dry-air mole fractions in the atmosphere, with fine spatial resolution ($\sim 20 \times 20$ m^2) mapped over large swaths ($\sim 100 \times 100$ km^2) in a single flight. The results provide confidence that MethaneSAT can make such measurements at unprecedentedly fine scales from space ($\sim 130 \times 400$ m^2 pixel size over $\sim 200 \times 200$ km^2 target area), thereby delivering quantitative data on basin-wide methane emissions.

RC: ***42: Including a table comparing the specifications of MethaneAIR to MethaneSAT at this point would be helpful.***

AR: This can be found in Chulakadaba et al. (2023). We cite this with reference to the table in the updated manuscript

> In preparation for MethaneSAT's launch, an airborne precursor called MethaneAIR has been constructed (Staebell et al., 2021), with near-identical instrument specifications (Table S1, Chulakadaba et al. (2023)).

RC: ***61: Consider to mention that scattering effects are more pronounced at shorter wavelengths, thus the 1.6 m band is more affected than the 2.3 m band in TROPOMI.***

AR: Whilst this is true, we mention the target band only to state that the proxy method is not possible. The main point of the paragraph was that the proxy method generally has a higher per-pixel retrieval success rate.

RC: ***64: You mention data from aircraft but also refer to satellite platforms.***

AR: The sentence does already distinguish between the aircraft and satellite based instruments (bold for emphasis)

> Recently instruments designed to detect high concentrations of CH_4 in individual methane plumes have been deployed **on aircraft**(AVIRIS-Thorpe et al. (2012), AVIRIS-NG-Thorpe et al. (2016), HySpex-Hochstaffl et al. (2023)) **and satellites**(Sentinel 2-Varon et al. (2021), GHGSat-Jervis et al. (2021), CarbonMapper-Shivers et al. (2021), PRISMA-Guanter et al. (2021), EnMAP-Roger et al. (2024)) to estimate emission rates from point sources.

RC: ***65: Does this relate even more to the precision requirement?***

AR: The AVIRIS like sensors typically have large biases (10-100 ppb XCH4) that strongly correlated to surface, as at such coarse spectral resolutions the surface cannot be easily disentangled from methane absorption.

At spatial scales beyond 1-10m, such biases would remain, by most sources would produce enhancements smaller than them. This is why we emphasize that it enables loosening the accuracy requirement.

RC: ***94: How do MethaneSAT's 20-30 revisits per year impact its claim or capability for monitoring?***

AR: Whilst MethaneSAT will be able to contribute to anomalous event reporting by partnering with organizations such as the UN IMEO program, a chief aim of the mission is to determine how methane emissions from each major production basin evolve over time (e.g. as verification that producers are meeting their COP pledges). The planned 10-20 revisits per year should be enough to detect changes associated with changes from improvements in infrastructure and production practices.

RC: ***104: Am I right that strictly speaking, it is the primary retrieval method used to infer concentration enhancements (which are then used in the emission inversion).***

AR: Yes - this is now clarified in the updated manuscript

> Here we present results from the maiden flight campaign of MethaneAIR using the operational MethaneSAT CO_2-proxy XCH_4 retrieval. This is expected to be the primary XCH_4 product used in subsequent emissions inversions

RC: ***109: Review the phrase "sensor rate spatial coverage."***

AR: Fixed - it should be "sensor's spatial coverage rate"

RC: ***Fig. 2: Consider specifying what constitutes a "typical measurement" in terms of photon radiance or another metric.***

AR: The manuscript has been updated to reference the albedo used in the simulation.

> Example transmission spectra for a typical MethaneAIR observation (0.3 Lambertian albedo, 30° solar zenith angle).

RC: ***165: Clarify what is meant by "an additional set of weaker lines overlap with the C."***

AR: There are more CO2 lines in the same wavelength range covered by the R branch of the CH4 band. I'm not sure how to write this more clearly.

RC: ***231: Does the initial estimation of surface albedo consider only a single pixel?***

AR: It is done for each pixel. The manuscript has been updated to clarify this.

> The *a priori* Lambertian surface albedo for each pixel is computed using the transparent region of the observed radiance at 1622 nm, assuming a non-scattering atmosphere.

RC: ***Sec. 4.1: I suggest making the section more concise.***

AR: The discovery and correction of the instrument defocusing induced by the unstable temperature environment was a big retrieval challenge. The section is long because the origin had to be investigated, and the impact on XCH_4 bias carefully characterized.

RC: ***Fig. 5: Label the squeeze factor next to the colorbar in (c1), similar to how ppb is labeled in (c2). What cross-track index is displayed in (c2)?***

AR: I have updated the colorbar label in c1 (x_{sqz}) I am not sure what is meant by the second sentence. The x-axis corresponds to the cross-track index of the detector.

RC: ***274-279: This passage could be rewritten for better clarity.***

AR: The passage was written as a suggestion by reviewer 1.

RC: ***393: The reference in Fig 11 to XCH4 being constant within 50 km is not entirely convincing (though it remains reasonable).***

AR: Provided that there is a similar albedo variation across the 3-min segment the XCH4-albedo anomaly should still be detectable. The TROPOMI analysis from which the figure is based was performed over much larger geographic areas (5 degrees latitude).

RC: ***394: Consider the potential issues of relying on data from a single pixel, even if it's only for an a priori estimate.***

AR: The value is the binned mean (red line) for the mean of all pixels within the 0.19-0.21 albedo bin (the red line in Figure 12). The 2-sigma sample mean uncertainties (dashed red lines) are also shown in the figure. The uncertainty is negligible.

RC: ***395, Fig. 12: Would using the median be a more robust measure than the mean?***

AR: In general yes, but Fig. 12 also shows the data density - there appears to be no outliers. Thus the mean and median are quite similar.

RC: ***Fig. 12: Consider adding a colorbar.***

AR: A colorbar has been added to the figure in the updated manuscript

RC: ***395: Ensure consistency; the text mentions computing the mean from a 0.02 width bin, but the figure caption refers to 0.1 width, while the gray lines represent 0.02 binned averages.***

AR: The text says a 0.02 width bin centered at 0.2, and the figure says the bin covers the range 0.19-0.21. This is the same. The text is not referring to the grey lines, but the specific bin at 0.2.

The red and grey lines correspond to all the binned averages. The text is updated to say this more clearly.

> The grey and red lines show the binned averages computed in 0.02 albedo increments before and after cloud screening respectively

RC: ***Fig. 13: Please describe the units of the colorbars.***

AR: The updated manuscript includes labels for the colorbars in the figure

RC: ***426: Given the importance of the 35 ppb finding, consider adding a statement relating this to Section 2.1 of the attachment. Also, think about moving the precision finding of 35 ppb to Section 5.3, as it is based on data presented in that section.***

AR: We have updated the manuscript to refer to Section S2.1

> The previous section showed that the main error in the flight retrievals is random noise. We estimate the precision of the 5×1 aggregated retrievals of 35 ppb, by taking the standard deviation of the XCH_4

> retrieved over background locations used in Figure **??**. This value is consistent with our estimate for the native resolution of MethaneSAT (Section S2.1), which has similar SNR to the 5×1 aggregated MethaneAIR retrieval. These noise levels reduce MethaneAIR's ability to detect small-scale XCH_4 gradients.

RC: ***430: How is the smoothed image 'g' calculated?***

AR: By finding the g that minimizes equation 8, as written in the text.

RC: ***Fig. 15: Consider to ensure that the colorbars have specified lower and upper bounds. Also, consider specifying time in hh:mm:ss format as done in Fig. 17.***

AR: We have updated the figure based on the reviewer suggestions

RC: ***514-515: Clarify why the detection limit of 121 kg/h and the quantification limit of 200 kg/h are considered consistent.***

AR: It is similar in magnitude but lower than the quantification limit. That is all that is meant by that statement.

RC: ***496: This point suggests a broader issue regarding the estimation of average emission rates from irregular revisits. Consider adding a brief discussion on this topic in the discussion section.***

AR: The subject of source intermittency on day-by-day timescales is discussed elsewhere in the literature (e.g. Cusworth et al. (2021)). The point we are trying to make is that since are detecting disconnected methane plumes, this will cause complications for the emissions inversion, whereby any source of methane is considered to be emitting at a constant rate over the course of the observation period. It is an unintended consequence of having accurate XCH_4 data at fine spatial scales, and must be considered by the emissions inversion model.

RC: ***500: Provide at least one argument or reference to support this statement.***

AR: This is based on the scale of the disconnected plume O(1 km^2), the size of the enhancement (O(10 ppb)) and the spatial resolution (O(10×10 m^2) and O(100×100 m^2))/precision (35/30 ppb per pixel) of both instruments. At the scale of the enhancement there are O(10^4) and O(10^2) pixels, which means the precision over the enhancements is 0.03 and and 3 ppb respectively, well below the size of the disconnected plume in both cases.

We have updated the line

> We see here that they are observable by MethaneAIR and should be detectable by MethaneSAT, based on the size of the observed enhancement and the spatial resolution and precision of both sensors.

RC: ***Fig. 19: Discuss any implications for the IME method if the swath cuts the plumes. Adjust the axis labels and colorbar font sizes for better readability.***

AR: The figure caption has been updated to indicate that partially-observed plumes will have their emissions underestimated.

> The IME method currently does not account for the impact of partially observed plumes; Such cases will lead to emission underestimates.

The size of colorbar/axes labels in Fig. 19 have been increased in the updated manuscript.

RC: ***Fig. 20: Increase the colorbar font size.***

AR: The colorbar font size has been increased in the updated manuscript

RC: ***S1.2: Briefly explain why the a priori profile pressure and temperature levels are dependent on the a priori surface and tropopause pressure, and how these coefficients are determined.***

AR: The coefficients are from the same vertical grid parameterization used by the University of Leicester GOSAT CO_2 retrieval. They are chosen to be compatible with the corresponding CO_2 and CH_4 a priori covariance matrices. We have updated the supplement as follows:

> The coefficients a_l,b_l, and c_l are those used by the University of Leicester GOSAT CO_2-Proxy retrieval (Parker et al., 2020), and are provided below:

For the retrieval there is an advantage of including the tropopause pressure in the vertical grid parameterization because the stratospheric/tropospheric concentrations are not expected to correlate with one another due to the slow vertical transport timescale.

RC: ***Eq. (S9): Describe how the optical depths are adjusted for an adjusted temperature.***

The text after equation 9 is updated to explain this

> The main effect of temperature is changing the absorption cross sections. In the retrieval the absorption cross sections are re-interpolated from their lookup tables each iteration to account for changes from the pressure/temperature state vector elements.

RC: ***Eq. (S8): Shouldn't the ratio yield a sigma coordinate on the left-hand side?***

Although the initial pressure profile is defined with the surface/tropopause pressure hybrid grid, the pressure is optimized using sigma coordinates. This is already explained in the supplement immediately before the equation

> Whilst the initial pressure grid uses the hybrid parameterization in the previous section, surface pressures are optimized using sigma coordinates.

RC: ***S2.3.2: Clarify whether the RR method is only feasible for aggregated pixels since single pixels cannot be divided into upper and lower halves. Explain the rationale for choosing upper/lower division over left/right.***

As explained in the text, the RR for the along-track half-pixels was estimated by linear interpolation between the observed albedos, assumed to be at the pixel centers.

> Since the scene is at the retrieved resolution, we have estimated RR via linearly interpolating the albedos between pixels in the along track direction.

We argue that because this strongly correlates to the actual retrieved wavelength shifts, that this is a reasonable metric for assessing the degree of inhomogeneous illumination. The reason for choosing the along-track direction is that this is the direction that impacts the ISRF for our instrument. For more theoretical details, Appendix by of Landgraf et al. (2016) applies here. I have added a line indicating why we make this choice

The inhomogeneity can be quantified by dividing each pixel in the along-track direction into a lower and upper half (indexed l and u respectively). The pixel is divided in the along-track direction because this is the direction that strongly impacts the ISRF.

RC: ***S2.3.2, Fig. S10: Consider using colorbar annotations instead of titles for consistency.***

AR: The figure in the updated manuscript now has the labels as suggested

RC: ***Fig. S12: Confirm whether "Pixel Mean XCH4 Enhancement" is the correct label for the colorbar. Should it instead indicate enhancement in the plume, affecting the error depending on the plume's prominence?***

AR: The figures actually correspond to the pixel-mean enhancement. e.g. if pixel mean enhancement is 100 ppb and the plume area fraction is 50%, this means the plume concentration will be 200 ppb. Each line corresponds to the same overall concentration enhancement - the x-axis indicates how it is distributed within the pixel.

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