Author response to Referees

Thank you to the Editor and reviewers for their helpful and constructive comments. We have made fairly substantial revisions to the manuscript in response. A brief summary of the main changes is provided here, while detailed responses to each referee are given below. Where comments overlap, relevant responses may also be found in other referee responses.

Summary of key revisions

Animal numbers (Anonymous Referee #1 and #3):

Added Climate TRACE livestock data and recalculated per-animal emissions. Results are now presented using two alternative activity datasets, and interpretation has been revised to focus on robustness of patterns rather than absolute values.

Background treatment (Anonymous Referee #1):

Clarified that no explicit background subtraction is applied. Wavelet denoising is used only for plume detection, and fluxes are calculated from the original XCH_4 field. Residual background variability is retained and may contribute to uncertainty.

Uncertainty and robustness (Anonymous Referee #1 and #2):

Clarified that the reported uncertainty reflects the consistency of DI flux estimates across integration box sizes, rather than a full error budget. Additional sources of uncertainty (wind, retrieval, background) are acknowledged but a full error propagation is not performed. Interpretation has been shifted to the population level, and detection bias is now discussed explicitly (Section 3.5).

Comparison with prior studies (Anonymous Referee #1):

Revised Table 1 to show representative emission ranges rather than a direct method comparison. Distinctions between annual inventories, campaign measurements, and instantaneous observations are now made explicit. The McCabe et al. (2023) entry has been corrected and IPCC/EPA differences clarified.

DI detection limit (Anonymous Referee #1-3):

Clarified that the DI method is used only after plume detection and that its intrinsic detection limit is unchanged. Plumes below the nominal limit are included only when meeting the robustness criterion and are interpreted at the population level.

Scene size (Anonymous Referee #3):

Added justification for the ±0.02° (~2 km) scene size, including discussion of trade-offs between plume capture and background variability.

Method description ("operational blueprint", Anonymous referee #3):

Expanded Sections 2.3 and 2.4 to clarify the targeted scene approach, wavelet denoising, and DI application. Limitations of the approach are now explicitly discussed.

Detection bias (Anonymous Referee #1–3):

Added a dedicated discussion (Section 3.5) showing that the analysis is conditional on detection and likely biased toward higher emission events.

Facility-scale emissions (Anonymous Referee #3):

Added a new Results figure showing total scene emissions (kg CH_4 h^{-1}), independent of livestock assumptions.

Interpretation of per-animal emissions:

Revised language throughout to emphasise that results represent detectable conditions and are not directly comparable to annual-average emission factors.

Additional revisions related to referee comments

Added a results figure showing scene-total methane emissions (kg CH_4 h^{-1}) prior to per-animal normalization.

Included a short explanatory statement clarifying that per-animal normalization is used to facilitate comparison with EPA inventory emission factors and prior aircraft and satellite based studies.

Revised Interpretive language throughout the manuscript to emphasize robustness and consistency across normalization choices rather than reliance on a single activity dataset.

Corrected typographical errors, figure inconsistencies, and wording issues identified by the reviewers.

Response to Anonymous referee #1

We thank the referee for their careful reading and insightful, constructive comments, which have greatly strengthened this work. Here we respond to each comment in detail.

Major Comment 1: Use of maximum permitted capacity as a proxy for animal numbers

Response:

We agree that permitted capacity is an imperfect proxy for animal numbers. To address this, we made three changes.

First, we added an independent livestock dataset from Climate TRACE and recalculated per-animal emissions. These estimates are generally higher than CDPHE capacities, leading to lower per-animal emission values when used for normalisation.

Second, we now present the two datasets as alternative activity estimates rather than implying a single correct denominator, and have revised the text accordingly.

Third, while absolute values depend on the dataset used, the overall patterns are consistent. dairy emissions remain higher than beef, and per-animal values frequently exceed EPA factors under detectable conditions even when using Climate TRACE.

We've updated the Results, figures, table, abstract, and conclusions to reflect this more clearly.

Major comment 2: Background methane field removal and spatial correlation of residuals

Response:
We agree the original description of background handling was unclear. We have revised Section 2.4 to make this explicit.

Wavelet denoising is used only to suppress high-frequency noise and improve plume detection. A 2D discrete wavelet transform separates each scene into low- and high-frequency components, and only the high-frequency component is removed. No explicit background field is estimated or subtracted, and large-scale methane structure is retained.

Flux calculations are performed on the original (non-denoised) XCH_4 data using plume masks derived from the denoising step. This avoids introducing artefacts from background correction, but means that residual background variability contributes to the overall uncertainty. We note that residual background variability is retained in the flux calculation, but inspection of individual scenes did not indicate systematic large-scale gradients dominating the plume signal at the scene scale.

We have clarified this workflow in the Methods and noted its implications for flux estimation.

Major comment 3: Uncertainty quantification and robustness criterion

Response:

We agree that the <100% relative uncertainty threshold is permissive and does not imply high-precision quantification for individual plumes. In this study, the reported uncertainty reflects only the variability of DI flux estimates across the growing-box series and is intended as a measure of solution stability rather than a full error estimate.

We now clarify that "robust" plumes should still be interpreted cautiously at the individual level, particularly near this threshold, and that comparisons with EPA emission factors are most meaningful at the population level, where aggregation reduces the influence of high uncertainty in individual detections.

We explicitly acknowledge that additional sources of uncertainty—particularly wind field error, retrieval precision, and background variability—are not included and likely dominate the total error budget. A full error propagation is not undertaken given the observational nature of the dataset and lack of validation data, so reported uncertainties should be interpreted as lower-bound estimates.

These clarifications have been added to the Methods and Results sections and the implications of detection bias are now discussed explicitly (Section 3.5)

Major Comment 4: Comparison with prior studies (Table 1)

Response:
We agree the original Table 1 could be read as a direct comparison between methods. We've revised the table and text to make it clear it's just showing typical emission ranges, not a validation.

The table now separates annual inventory values from campaign and instantaneous measurements, and the caption highlights the differences in how these are derived.

We've also updated the McCabe et al. (2023) entry to include only beef, as dairy was only minimally represented. We now note that IPCC Tier 2 values are national defaults, while the EPA values are state-specific.

MethaneAIR values are labelled as averages from robust plume detections under detectable conditions, i.e. snapshots rather than annual averages. These changes improve clarity and address the reviewer's concerns.

Minor Comments

6. Lines 103–106: DI detection threshold (500 vs. 120 kg h $^{-1}$)

We clarify that the DI method itself is unchanged. Improved detectability comes from targeted scenes and preprocessing, not a lower intrinsic limit. We now state explicitly that no single detection threshold is defined, and that detectability depends on emissions, wind, and background conditions.

7. Figure 6 and Section 3.1: Detection threshold curves

We clarify that the x-axis shows expected emissions based on animal numbers and EPA factors. These are used only to group facilities by approximate emission strength and are not independent observations.

8. Lines 257–260: Averaging of "robust, disconnected, non-unique plumes"

We clarified the definitions of unique and non-unique plumes in the Methods and how they are combined to avoid double counting in scene totals.

9. Section 4, Lines 371–378: Overstated causal interpretation

We agree the original wording was too strong. The revised text avoids causal claims and presents possible explanations more cautiously, including uncertainty in animal numbers and detection bias.

Response to Anonymous referee #2

Thank you for your time and your thoughtful and constructive comments. These have helped to improve the clarity of the manuscript. We address each point in detail here.

- How is a detection of None determined?

We have clarified the detection classification used in Fig. 7 (formerly fig.6) . Expected CAFO emissions are derived from animal numbers and EPA emission factors and are used only to group facilities by estimated emission strength. The classification has been updated to "None Detected" which indicates that no plume meeting the detection criteria was identified within the scene. This distinction has been added to the manuscript to clarify that non-detection does not imply absence of emissions.

- How are wind fields handled, since the methane is a column-averaged quantity?

We have clarified in Section 2.4 that winds are taken from the HRRR model and applied within the DI framework, which operates on column-integrated quantities. Wind direction is additionally constrained using plume orientation to improve consistency between transport and observed plume structure. We also noted that wind uncertainty remains a dominant source of error in DI-derived flux estimates and is not fully captured in the reported uncertainty.

- Echo Referee 3 Comment #2 regarding bias towards stronger plumes

We agree that filtering based on robustness may bias the dataset toward stronger emissions. This is now explicitly discussed in Section 3.5, where we show that the analysis is conditional on detection and likely biased toward higher emission events. Results are interpreted as representative of detectable plume conditions rather than average facility behaviour

- Echo Referee 1 Comment #3 on uncertainty budget

We agree that the reported uncertainty reflects only the variability of DI flux estimates across box sizes. The manuscript now explicitly states that additional sources of uncertainty, including wind field error, retrieval uncertainty, and background variability, are not included and likely dominate the total error. Some of the variation in the DI flux estimates reflects changes in wind and retrieval noise across the integration boxes, and would be lower under smoother conditions. Reported uncertainties are therefore interpreted as lower-bound estimates, and results are emphasised at the population level.

- Figure 6: (now figure 7):

We have clarified that the x-axis represents expected emissions derived from animal numbers and emission factors, rather than MethaneAIR-derived values. The text now explicitly distinguishes expected emissions from observed plume detections to avoid confusion.

- Figure 7: Is Farm ID part of the CDPHE data? It is not specifically mentioned

We have clarified in the Methods that Farm IDs are internally assigned identifiers used for tracking CAFO locations and are not part of the original CDPHE dataset. It is also no longer used as an identifier on this figure.

Response to Anonymous referee #3

We thank the referee for their careful and constructive review which has helped to strengthen the manuscript. We respond to each of the main comments below. Where relevant, related points are also addressed in the responses to other referees.

Major Comment 1: Method description, evaluation, and DI applicability

We agree that the original manuscript did not sufficiently describe the method and its implications. Sections 2.3 and 2.4 have been revised to provide a clearer and more detailed description of the targeted scene approach, wavelet denoising, and DI application.

The ±0.02° (~2 km) scene size is now justified as a balance between capturing near-field plume structure required for DI flux estimation and limiting background variability. We also note that a fixed scene size is not optimal under all conditions and discuss this limitation.

Wavelet denoising is now described more explicitly as a method for suppressing high-frequency noise and generating plume masks, while retaining large-scale methane structure. Additional filtering steps are applied to reduce false detections. Flux calculations are performed on the original XCH_4 data.

With respect to the DI method, we clarify that we do not attempt to lower its intrinsic detection limit (~500 kg h^{-1}). Instead, DI is used only for flux estimation after plume detection within targeted scenes. Targeted subsetting and denoising improve detectability of weaker plumes but do not modify the DI formulation itself. Plumes below the nominal detection limit may be detectable under favourable conditions but are not always robustly quantifiable. These are only included when they meet a consistency-based robustness criterion and are interpreted at the population level.

We also explicitly state that no single detection limit is defined for the combined method, and that detectability depends on emission strength, wind, background variability, and scene characteristics.

Major Comment 2: Potential bias toward high emissions

We agree that the robustness filtering introduces a bias toward higher emission events. This is now explicitly discussed in Section 3.5. The analysis is conditional on detectable plume conditions, and lower-emission events are likely underrepresented.

We emphasise that MethaneAIR-derived per-animal emissions represent detectable emission conditions rather than time-averaged behaviour, and that differences relative to EPA/IPCC values likely reflect a combination of detection bias, activity data uncertainty, and real variability.

Interpretive statements throughout the paper have been revised to reflect this more cautious approach.

Major Comment 3: Interpretation of beef vs EPA comparison

We agree the original wording was inconsistent. The manuscript has been revised to ensure a consistent interpretation. We now state that MethaneAIR-derived emissions for beef CAFOs are frequently above EPA values under detectable conditions, and avoid implying agreement where it is not supported by the results.

Major Comment 4: Lack of facility-scale emission context

We agree that facility-scale emissions provide important context. A new figure showing scene-total methane emissions (kg CH_4 h^{-1}) prior to per-animal normalisation has been added. These values are independent of livestock assumptions and provide a direct view of the magnitude and variability of emissions at the facility scale.

We retain per-animal normalisation to enable comparison with inventory emission factors and prior studies, but now clarify its limitations and dependence on livestock data.

Minor comments

We thank the reviewer for the detailed minor comments. The manuscript has been revised accordingly:

- Abbreviations (e.g. CAFO, oil and gas) are now defined consistently at first use.
- Additional context has been added to better position this work relative to previous aircraft-based agricultural methane studies.
- Figure captions and labelling (e.g. Fig. 1 panels) have been corrected.
- Minor typographical and formatting issues have been corrected.
- Clarifications have been added where needed.
- Speculative statements have been revised to be more cautious or removed where unsupported.