We would like to thank the two Referees for the constructive comments on our manuscript. Please find our point-by-point reply below.

Anonymous Referee #2 (Major revisions)

GENERAL COMMENTS

The manuscript presents a novel automatable method for identifying contrails embedded in cirrus clouds from airborne lidar observations. The detection of embedded contrails inside cirrus clouds is at present high up on the agenda, and therefore this method makes a very timely contribution to an active research field.

The described method uses the particle backscatter coefficient b and the particle linear depolarization ratio d from the lidar system to define a contrail mask which can be used to identify embedded contrails in lidar observations. Suggested boundary values for separating embedded contrails from natural cirrus are $ß > 4\ Mm^{-1}\ sr^{-1}$, and $\delta < 30\%$ to 43%, depending in the conditions of the background cloud. The threshold values were deduced from the observations of the airborne WALES system onboard of the German research aircraft HALO during the field experiment ML-CIRRUS on mid-latitude cirrus clouds in 2014. The developed mask was then applied to the observations during the subsequent HALO field experiment CIRRUS-HL on cirrus clouds at high latitudes.

The method description in Chapter 2 is clear but the presentation of results and of the method validation in Chapter 3 requires clearer presentation and a better structured discussion. Details of requested changes will be discussed in the SPECIFIC COMMENTS.

Overall, the manuscript is well structured and fits very well into the scope of AMT. However, before being acceptable for publication it requires modifications of the presentation in general and of the explanation and discussion of results in particular. Suggested revisions are discussed in the following paragraphs.

Thank you for the positive assessment of our work. We have tried to improve the presentation of the results and validation as outlined in our replies to the SPECIFIC COMMENTS.

SPECIFIC COMMENTS

1| Throughout the manuscript there is a bit of confusion about the used terminology:

Contrail formation requires fulfillment of the Schmidt-Appleman criterion, according to Schumann (1996), independent of the environmental conditions or preexisting cloudiness. Persistent contrail existence requires ice-supersaturation of the embedding air mass. Following e.g. Kärcher (2018), climate-impactful contrail-cirrus develop from persistent contrails only, when they spread out into contrail-cirrus by wind shear perpendicular to the line shape of the persistent contrail, so that they cover a large area. That means, persistent contrails can exist for a long period but may have no climate impact as long as they keep their line shape. In contradiction to this concept, Figure 11 suggests that all persistent contrails develop into contrail-cirrus.

The reviewer is correct that we have been imprecise with some formulations. We have worked through the manuscript to improve the text as shown below. We have also revised Fig. 11 and its caption to clarify that large contrail age constitutes "*potential contrail cirrus can form when persistent contrails are spread out spatially as a result of wind shear.*"

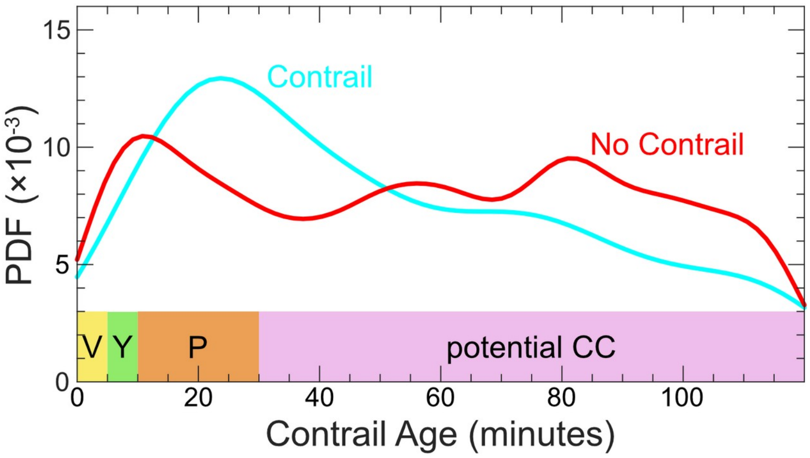

Figure 11. Probability density functions (PDFs) of the time delay between the passage of an aircraft through a cirrus cloud and the WALES lidar observation as a measure of contrail age. Data refer to the circles in Figs. 9 and 10 but for all WALES observations during ML-CIRRUS and CIRRUS-HL (see also Table 2). The colored bars mark different stages of the contrail life cycle: vortex phase (V, yellow), young contrails (Y, green), persistent contrails (P, orange), and potential contrail cirrus (potential CC, magenta) that can form when persistent contrails are spread out spatially as a result of wind shear.

Since this is not always the case, this differentiation needs to be reflected in the manuscript. Particularly on line 30, the statement "that the conditions for contrail formation are most often fulfilled in regions already covered with cirrus clouds (Petzold et al., 2025)" is not correct. The referenced study says that long-lived contrails exist most often in regions already covered with cirrus clouds. This is a significant difference and needs to be corrected. That can be achieved easily by rephrasing "that the conditions for existence of climate-impactful long-lived contrails are most often fulfilled for regions already covered with cirrus clouds (Petzold et al., 2025)".

As suggested, the statement in line 30 has been revised to:
"Airborne in-situ measurements show that the conditions for the existence of climate-impactful long-lived contrails are most often fulfilled for regions already covered with cirrus clouds (Petzold et al., 2025)."

In the same context, the statement on line 305 saying that "While one might therefore expect that an aircraft that passes through a cirrus cloud automatically forms an embedded contrail, we rather find that most cases don't" needs to be corrected. The formation of a contrail, also inside a preexisting cirrus cloud, still requires the fulfillment of the Schmidt-Appleman criterion which, however, must not always be the case inside a dissolving cirrus cloud which exists at ice-subsaturation. In such a case, no contrail will form since the conditions are not fulfilled. Only if the aircraft passes through an air mass close or above ice-saturation (PCCR and ISSR, following the terminology used by Petzold et al. (2025)) the conditions for contrail formation are fulfilled and a contrail will form which may develop into an embedded contrail-cirrus. The authors may of course find many cases of aircraft passing through an existing but dissolving cirrus cloud and no contrail will form because the air mass is not humid enough. Therefore, Section 3.6 requires substantial revision.

Section 3.6 has been revised as suggested. Specifically, the first paragraph now reads:
"Figures 9 and 10 show a large number of red circles that refer to intercepts for which no contrail signature was identified in the manual analysis. In general, those cases are also classified as background in our masking and we consider them to represent true negatives. Petzold et al. (2025) show that potential contrail-cirrus regions (PCCRs) almost always coincide with regions that are

already covered with cirrus. They define PCCRs as air masses with a relative humidity over ice larger or equal to 90% for which the Schmidt-Appleman Criterion (SAC, Schumann, 1996) is fulfilled. However, this does not imply that all cirrus regions are also PCCRs and that an aircraft that passes through a cirrus cloud automatically forms an embedded contrail. For instance, a dissolving cirrus at ice-subsaturation might support contrail persistence but will not promote contrail formation.

For our cases of contrail absence, true negatives might refer to conditions for which SAC is not met. Alternatively, …."

2| Section 3.3 on the validation of the contrail mask is very difficult to understand. It is presented as a long but a bit unstructured text section. Adding sub-headings may help to give a structure to this section.

Thank you for this suggestion. We have added the subsection "*Validation approach and importance of PLDR conditions*" and "*Results for selected cases*".

We now also state that variations in the thresholds and the feature-size constraint for the entire data set are discussed in Sect. 3.5:
"*The effect of variation in the thresholds for β and δ as well as for the feature-size constraint and the detection of embedded contrails for the entire data set are discussed in Sect. 3.5*."

What is meant by the term "unrelated" in line 191? If it means "independent of" then it may be rephrased to make the message clearer.

The corresponding statement has been revised to:
"*Observations with combinations of β and δ that fall in the perturbed sectors in Fig. 8 are not always related to embedded contrails.*"

Same for line 202 where the term "resort" is not clear. It is suggested to rephrase this sentence for the sake of clarity.

Resort has been replaced with go back to.

3| The presentation of important results of this study in Figures 2 and 8 suffer from a "diffuse" presentation. In Figure 2, the "clean" and "polluted" cases are hardly identifiale given the chosen color scheme. Adding contour lines or selecting another color scheme may improve these figures and may make the contained information more visible. In Figure 8, extracting the relevant information is even more difficult. In Figure 8a, there is no difference identifiable between perturbed and unperturbed cases. The inserted lines simply represent the threshold values but the consequences for the distribution of the observed cases are difficult to identify. It is recommended to re-work the presentation of the figures.

We have revised Figures 2, 8, and B2 as suggested by changing the color table and adding contour lines. The figures now look as shown below.

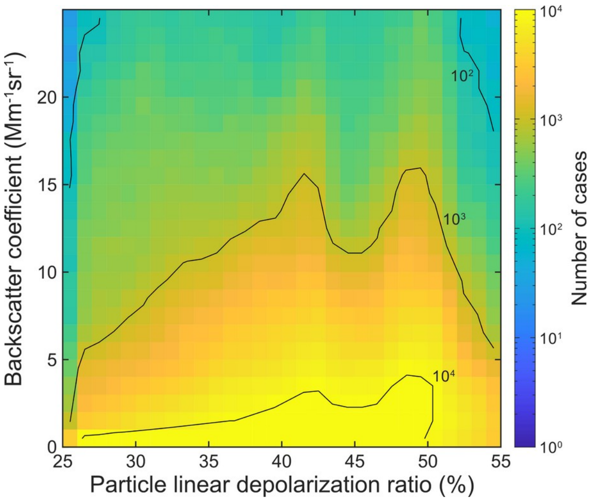

Figure 2. 2d histogram of particle backscatter coefficient (β) and particle linear depolarization ratio (δ) for the WALES cirrus observations during ML-CIRRUS.

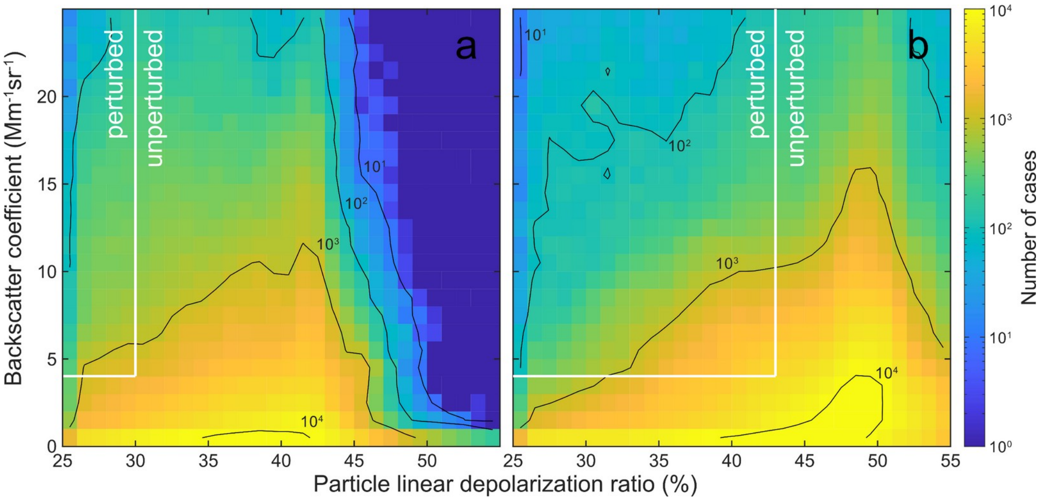

Figure 8. Same as Fig. 2 but for observations according to conditions with low PLDR (a) and high PLDR (b) as defined in Urbanek et al. (2018). The white lines mark the threshold values of $\beta = 4\ \mathrm{Mm^{-1}sr^{-1}}$ and $\delta = 30\%$ (low PLDR) / $\delta = 43\%$ (high PLDR) for separating perturbed cloud regions from the unperturbed background cloud in step one of the contrail mask.

MINOR ISSUES AND TYPOS:

- Abstract, 1st line: Please correct "through the emission of …"
- Abstract line 6: remove space character in the word "identifier".
- Line 63: correct presentation of references to Author et al. (Year).
- Line 81: Shouldn't that refer to Figure 2 instead of Figure 3?
- Caption of Figure 2: The properties b and d should be named explicitly so that the figure caption can be understood without having read the abstract where b and d are defined.
- Line 87: Suggested clarification if ERA5 information is meant: "in addition, ERA5 information on temperature, …"

- Line 97: A link to Flightradar24 may be added.
- Line 133: In the sentence “An example of this assessment is presented below” it should be specified where this information is given, e.g., which section, paragraph etc.
- Caption of Figure 6: Please explain the meaning of the yellow dots. They likely point to embedded contrails but that should be explained in the caption. I assume the last sentence of the figure caption refers to lidar profiles. If so, it should be made clear.
- Line 169: the term “Cases” should be written in lower case letters.
- Line 344: remove “)” after 50°C.
- Update reference list, namely Seelig et al. (2025) and Petzold et al. (2025).

Thank you for spotting these minor issues and typos. They have all been addresses and corrected.

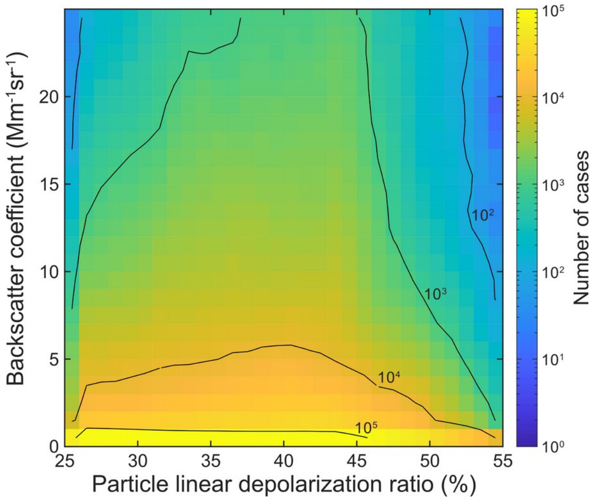

Figure B2. 2d histograms of particle backscatter coefficient (β) and particle linear depolarization ratio (δ) for the WALES cirrus observations during CIRRUS-HL.

REFERENCES

Kärcher, B.: Formation and radiative forcing of contrail cirrus, Nature Communications, 9, 17, 10.1038/s41467-018-04068-0, 2018.

Petzold, A., Khan, N. F., Li, Y., Spichtinger, P., Rohs, S., Crewell, S., Wahner, A., and Krämer, M.: Most long-lived contrails form within cirrus clouds with uncertain climate impact, Nature Communications, 16, 9695, https://doi.org/10.1038/s41467-025-65532-2, 2025.

Schumann, U.: On conditions for contrail formation from aircraft exhausts, Meteorologische Zeitschrift, N.F.5, 4-23, https://doi.org/10.1127/metz/5/1996/4, 1996.

Seelig, T., Wolf, K., Bellouin, N., and Tesche, M.: Quantification of the radiative forcing of contrails embedded in cirrus clouds, Nature Communications, 16, 10703, doi: https://doi.org/10.1038/s41467-025-66231-8, 2025.

Anonymous Referee #3 (Minor revisions)

General comments

The study presents an analysis of airborne lidar observations from the HALO research aircraft during the ML-CIRRUS (2014) and CIRRUS-HL (2021) campaigns to develop and validate an automated method for detecting contrails embedded within existing cirrus clouds. Using measurements of particle backscatter and depolarization ratios from the WALES lidar, combined with aircraft position data and ERA5 wind fields, the authors first identify and manually verify cases of embedded contrails and then derive a two-step detection algorithm based on physical thresholds and object-size criteria. The method is trained on ML-CIRRUS data and validated with CIRRUS-HL observations, showing good performance in identifying unperturbed cloud regions and reasonable skill in detecting embedded contrails, although with systematic overestimation, particularly under polluted (high-PLDR) conditions. The study further examines sources of misclassification, the influence of contrail age, and statistical occurrence rates, concluding that embedded contrails represent only a small fraction of cirrus observations but can be systematically detected using lidar data alone, providing a basis for future large-scale and synergistic studies of aviation-induced cloud perturbations.

While the methodological approach is well motivated and carefully implemented, there are several overarching issues that limit how confidently the results can be interpreted. Most importantly, the automated detection relies on thresholds derived from manual, intercept-based analysis, so the validation is only partly independent and the ground truth remains limited. Moreover, the detected “embedded contrails” are not clearly distinguishable from other small-scale cirrus perturbations (e.g., fall streaks), leading to substantial and acknowledged overestimation, especially under high-PLDR conditions, and raising questions about the robustness of the occurrence statistics. The method’s performance also depends strongly on fixed β, δ, and object-size thresholds, whose sensitivity is not systematically assessed, and on assumptions about depolarization signatures that may not hold across different contrail ages and temperature regimes. Finally, uncertainties in the advection-based matching and PLDR regime classification may further affect detection accuracy. Together, these points suggest that the product is best interpreted as a proxy for contrail-like perturbations rather than unambiguous embedded contrail identification, warranting more detailed discussion and quantitative assessment, as outlined in the specific comments.

Nevertheless, this study presents a timely and technically well-executed contribution toward the automated detection of aviation-induced perturbations in cirrus clouds using airborne lidar observations. The approach is clearly motivated and carefully documented. However, several methodological and interpretational aspects require further clarification and strengthening. Addressing these points through additional analysis and clearer discussion of the method’s scope and limitations would improve the robustness and impact of the study. I therefore recommend that the paper undergo revisions before publication.

Thank you for the overall positive assessment of our work. We have addressed the Referee’s concerns in our replies to the Specific comments.

Specific comments

Line 85: In Sect. 2.3, the description of the ERA5 data is rather brief. The authors should provide more detailed information on the temporal and spatial resolution of the reanalysis used and clarify more explicitly which ERA5 variables were applied in this study. In addition, the proper reference for ERA5 (Hersbach et al., 2020) should be used.

Hersbach, H., Bell, B., Berrisford, P., et al. (2020): The ERA5 global reanalysis. Q. J. R. Meteorol. Soc., 146, 1999–2049.

Thank you for the comment. The corresponding section has been revised to:
"*Meteorological profiles from the European Centre for Medium-range Weather Forecast (ECMWF) ERA5 reanalysis (Hersbach et al., 2020) are used in the analysis of the WALES lidar measurements. The hourly data provides a spatial resolution of 0.25° x 0.25° on 37 pressure levels between 1000 and 1 hPa. In this study, we use the zonal (U) and meridional (V) wind components to calculate wind speed and wind direction at intersection points of HALO and commercial flights at typical flight altitudes between 200 and 300 hPa. We consider an averaging period of 2 h in line with the time frame used for aircraft position matching. Wind speed and direction at the intercept of tracks from HALO and commercial aircraft are then combined with speed and heading of both aircraft to account for advection effects as described in the next section. Temperature, pressure, and relative humidity are extracted for further insight into the meteorological conditions at the intercept point.*"

Line 92: In Sect. 2.4, where the advection correction and intercept matching based on ERA5 winds are introduced, and in Sect. 3.2–3.3, where spatial offsets between masked regions and confirmed intercepts are discussed, the uncertainty associated with the advection correction deserves more quantitative treatment. Since the validation relies on predicted intercept locations, errors in wind fields, headings, and timing may contribute to both false negatives and apparent false positives. The authors might consider estimating and reporting an uncertainty range for the advected intercept positions and discussing how this uncertainty affects the interpretation of the detection performance.

Thank you for this comment. We agree that the current presentation of the intercept points in Figures 9 and 10 gives the impression that those are infallible findings. The location of the intercept point is strongly affected by the ERA5 wind field used for matching. For the error analysis added to Figure 9, we assume that wind direction is accurately represented but wind speed could be off by 1 m s^{-1}.

We have added the following text to Sect. 2.4:
"*The predicted position an intercept point depends on the accuracy of the heading of the two aircraft, the time difference between them as well as wind direction and wind speed at flight level. Of those, we consider wind speed to be associated with the largest uncertainty. Given a certain error in wind speed, the location error is exacerbated with increasing time delay. To assess this effect, we have repeated the intercept-point retrieval assuming 1 m s^{-1} error in wind speed.*"

We have furthermore added the following text to Sect. 3.2 at the end of the discussion of Figure 9:
"*Finally, the error bars on the location of the intercept points indicate scaling with the time delay between the two aircraft, i.e., the temporal difference dominates over the wind-speed error. Lowering the accepted time delay of currently 2 h would be a straightforward measure for reducing the error in the location of the projected intercept points.*"

The revised Figures 9 and 10 now looks like this:

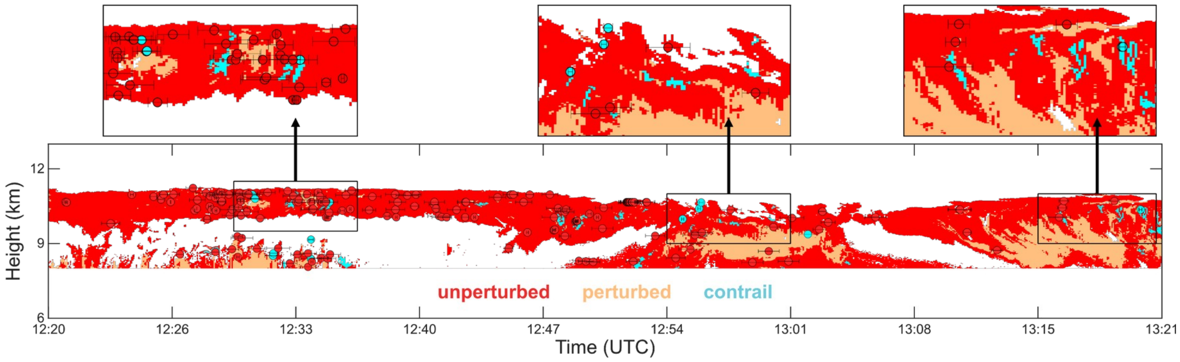

Figure 9. Result of applying the contrail mask to the observations in Fig. 6. Unperturbed cirrus regions identified in step one are marked in red. Perturbed cloud regions that pass the β-δ threshold (step one) but fail the heterogeneity criterion (step two) are marked orange here but re-labeled as unperturbed cirrus in the final masking. Perturbed cloud regions passing the heterogeneity test are marked in cyan. Dots refer to the matched cases in Fig. 6 that have been confirmed as contrails (cyan) or unperturbed cloud (red) in the manual analysis. Error bars represent the range of intercept locations related to assuming an error of 1 m s^{-1} in ERA5 wind speed. The insets in the top row represent close-ups of the regions marked by black boxes in the bottom panel.

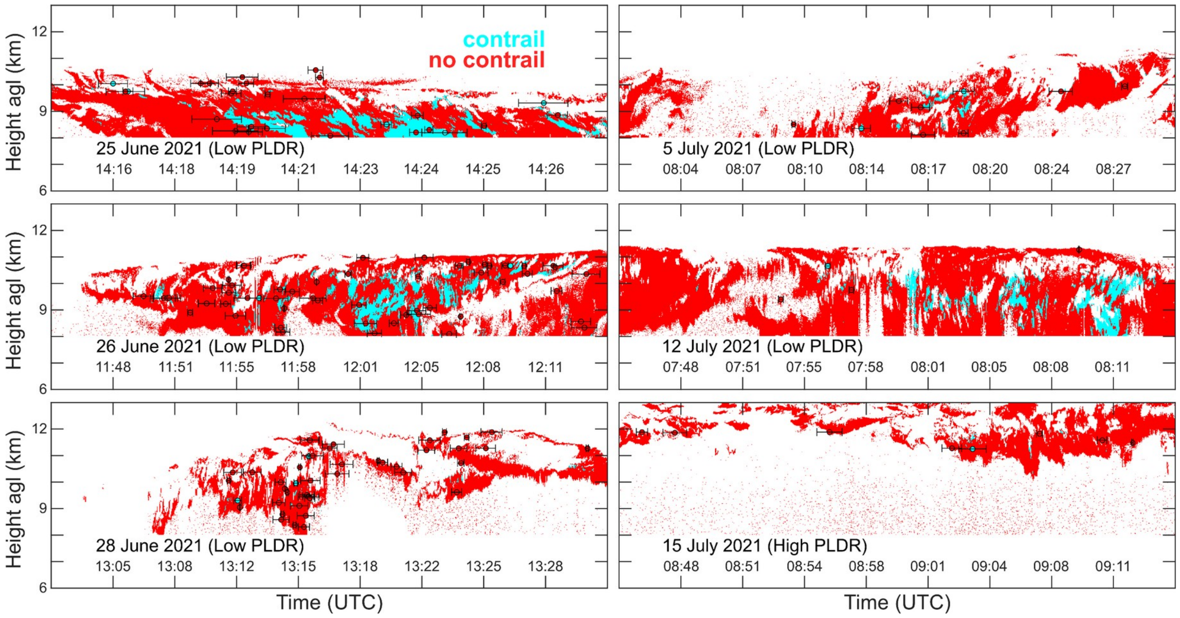

Figure 10. Same as Fig. 9 but for WALES observation of cirrus clouds during CIRRUS-HL and with orange regions in Fig. 9 reassigned to unperturbed cloud (red). Note that gaps in the cloud area at 10 to 12 km between 13:15 and 13:29 UTC on 28 June 2021 are due to detector saturation for signals from optically thick regions of the cloud.

Line 115: In Sect. 2.5, where the manual detection procedure is described, the authors may consider explicitly acknowledging that the thresholds used in the automated mask are derived from this by-eye, intercept-guided analysis and that the subsequent validation relies on a similar approach. While this is reasonable for method development, it implies that the evaluation is not fully independent. A brief discussion of this potential circularity and its implications for detection uncertainty and overestimation would improve the transparency of the methodology.

We now state explicitly that contrail cases are identified through by-eye inspection. We have furthermore added an Appendix C in which Table C1 presents the effect of different choices of threshold values on the number of detected contrails.

The following text has been added to Sect. 3.2:
"The robustness of the selected threshold values has been evaluated in a sensitivity analysis in which β is lowered to 3 Mm^{-1} sr^{-1} and δ is increased to 35% and 45% for low and high PLDR conditions, respectively. The comparison of contrail occurrence for different variations of threshold values is presented in Table C1."

This Appendix is also referred to in Sect. 3.5 when discussing Table 3.:
"Table 3 summarizes the statistics of identifying perturbations with the contrail mask for ML-CIRRUS and CIRRUS-HL. More details of the impact of the choice of threshold values and feature size are provided in Table C1."

Figure 5: The authors may consider adding the tracks of the relevant commercial aircraft (if feasible) and possibly the ERA5 background winds to better place the observations in context. In addition, it would be helpful to more clearly indicate the locations of the selected profiles discussed later in Fig. 6 and in the main text, as these are currently difficult to see.

Excellent suggestions. We have revised Figure 5 accordingly. It now looks like this:

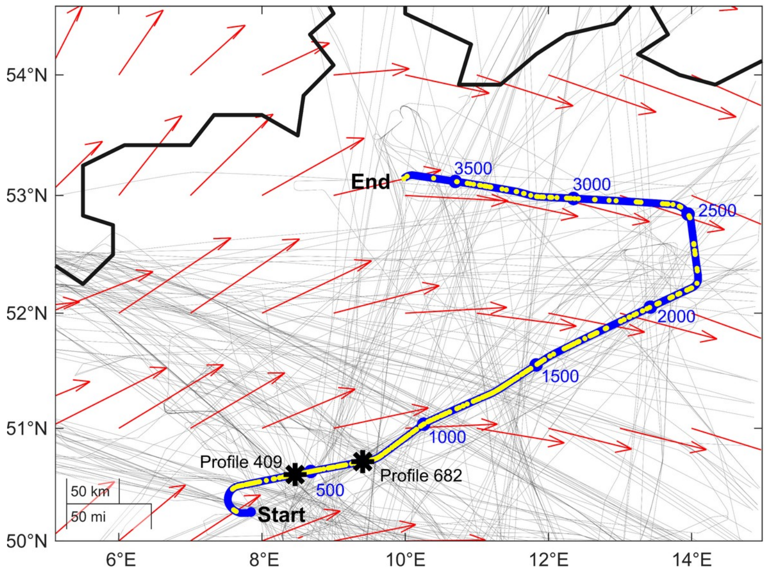

Figure 5. Overview of the location of about 1 h of WALES measurements along the HALO route (blue line with blue dots indicating intervals of 500 profiles) around noon on 1 April 2014 (magenta in Fig. 1). The yellow dots mark the location of advected intercept points with commercial aircraft passing through the region (thin gray lines) less than 2 h prior to the HALO observation (see Sect. 2.4). The ERA5 wind field is indicated by red arrows. Black rosettes highlight the location of the profiles shown in Fig. 7.

Line 178: Regarding the choice of the β and δ thresholds (e.g., β > 4 Mm^{-1} sr^{-1} and δ < 30%/43%), the authors should consider providing a quantitative sensitivity analysis to demonstrate the robustness of these values. Although the thresholds are physically motivated and derived from the ML-CIRRUS dataset, it remains unclear how variations in these parameters would affect detection performance, overestimation rates, and regime dependence. Exploring alternative threshold ranges and documenting their impact on the results would strengthen the methodological credibility and transferability of the proposed approach.

Please see our reply to comment on line 115 which also covers this comment.

Line 203: Where the object-size filter of 10–50 pixels is introduced, the authors should consider including a sensitivity analysis to assess the robustness of this choice. While the selected range is physically motivated and supported by empirical examples, it remains unclear how strongly the detection rates and overestimation factor depend on this specific threshold. Testing alternative ranges and quantifying their impact on true and false detections would strengthen confidence in the method.

Another great suggestion that we have followed up. We find that smaller feature sizes include lots of noise-related false detections while the inclusion of larger features changes contrail detection on the order of 10% in terms of detected features. These results have been added as Appendix C and a corresponding statement has been added to Sect. 3.2:
"*The result of allowing for smaller or larger feature size on contrail detection is shown in Table C1*."

Line 242: In Sect. 3.3, where the authors discuss detections during CIRRUS-HL that cannot be linked to aircraft and may be related to fall streaks or other in-cloud features, the ambiguity between embedded contrails and non-aviation-induced structures should be addressed more explicitly. Given that the stated goal is to enable detection without air-traffic data, the current method appears to identify "perturbation-like objects" rather than unambiguous embedded contrails. The authors may wish to clarify this limitation and discuss how it might be further mitigated.

The reviewer is correct and we have revised our language to note that detected features are not synonymous with embedded contrails. We added the following statement to Sect. 3.3 (in the part that is now Sect. 3.3.2):
"*In that context it is important to emphasize that the identified features are unambiguous embedded contrails but rather contrail-perturbation-like objects.*"

We have also revised the second paragraph of the summary to better account for these limitations:
"*The observations during CIRRUS-HL are used for assessing the output of the feature masking through comparison to a manual analysis of aircraft-track intercepts. We generally find a better performance of the feature masking during low-PLDR conditions, i.e., for cirrus clouds that have not already encountered earlier perturbations. Although the feature mask overestimates the number of objects, the factor of four compared to embedded contrails from by-eye inspection remains consistent across both ML-CIRRUS and CIRRUS-HL datasets, indicating a stable, first-order approximation of the detection error. It is important to note that, in terms of the optical signal, false positives cannot be distinguished from actual embedded contrails, as defined in step one of our mask. They thus represent contrail-perturbation-like objects rather than unambiguously detected embedded contrail. An increase in the lower size limit for object detection could close the gap in the number of detected features and verified contrails. However, features larger than 10 pixels are unlikely to be purely noise-related and are for now maintained in the subsequent analysis of the properties of embedded contrails due to their optical similarity to those features.* "

Line 335: In the Conclusions, where the systematic overestimation by approximately a factor of four is mentioned, the authors should consider providing a more thorough discussion of the origin, robustness, and implications of this uncertainty. In particular, it would be helpful to clarify to what extent this factor depends on the chosen thresholds, PLDR regime classification, and campaign-specific conditions, and how it propagates into the reported occurrence statistics and potential future applications of the method.

Please see our replies to the previous comment and the added text in which this concern is also addressed.

Technical corrections

Please ensure that abbreviations (e.g., Figure/Fig., Section/Sect.) follow the Copernicus manuscript guidelines and are used consistently.

Please avoid contractions (e.g., “don’t,” “doesn’t,” “haven’t”) to maintain a formal writing style.

The title of Subsection 3.6 should be rephrased in a more formal and descriptive manner.

Line 1: Rephrase as “emission of CO_2”?

Line 7: There appear to be superfluous spaces within individual words.

Line 81: Reference to “Figure 3” should be replaced by “Figure 2”.

Line 81: Abbreviation PLDR was not introduced.

Line 169: “Therefore, _c_ases…”

Line 302: Start sentence with “Figures 9 and 10 show…”

Line 344: Remove “)” after −50 °C.

Thank you for spotting these minor issues and typos. They have all been addresses and corrected.