EGUSPHERE-2024-3398

Peer Review - Megill and Grewe, "Investigating the limiting aircraft design-dependent and environmental factors of persistent contrail formation".

Author Responses: First Round

We thank the reviewers for their very valuable feedback. With their help, we believe that we were able to significantly improve the quality and impact of our work. We have addressed all comments on a point-by-point basis below and updated our manuscript accordingly. We have submitted a revised manuscript as well as a track-changes version, in which additions are indicated in blue and deletions in red. Unless specifically stated, our references to line numbers refer to the revised manuscript (without track-changes).

We would like to address two significant changes that we made to our manuscript.

1. **Updated methodology of the droplet formation limiting factor**
   Since uploading the pre-print, we have reconsidered the issue briefly discussed in ln. 144-148 of the original pre-print: With our original methodology, we were unable to capture the lower "effective freezing temperature", notably shown by Bier et al. (2022, 2024) for both conventional as well as hydrogen combustion aircraft. This resulted in an overestimation of the potential persistent contrail formation for high-G aircraft and an asymptote at $G >$ 4.29 Pa/K.

   What we did not consider in the original methodology, is that for ice crystals to form, the plume must be *concurrently* supersaturated with respect to water and below the homogeneous freezing temperature. If the plume is subsatured with respect to water again before the homogeneous freezing temperature is reached, the water droplets would likely evaporate before they could freeze (see e.g. Figure 3 of Bier et al., 2024). Consider Figure 1 of the original pre-print: For an aircraft with $G =$ 3.7 Pa/K at ambient conditions defined by the green point for droplet formation, the mixing line would drop below the water saturation curve before it crosses the 235.15 K boundary. We thus realised that defining T_{max} as the temperature at which the threshold mixing line is tangential to the water saturation curve is insufficient for high-G aircraft.

   Instead, we suggest modifying the definition of T_{max} such that it is equal to 235.15 K when it would otherwise be greater than 235.15 K (see Eq. (5) of the new manuscript). This occurs for $G >$ 2.38 Pa/K. In this way, we ensure that all possible mixing lines are at some point concurrently supersaturated with respect to water and colder than 235.15 K (see the new Figure 1 for $G =$ 6.0 Pa/K). Using this method, we were also able to closely replicate the ambient temperatures at which Bier et al. (2022 & 2024) found ice crystal numbers of zero (their Figures 5(c) and 4 respectively). We show this in the new Figure S1.

   We appreciate that this - much like the Schmidt-Appleman Criterion in general - is only an approximation and that, in reality, the formation of contrails depends on many microphysical processes. The mixing process does not, in reality, follow the straight lines shown in Figures 1 and S1. However, we believe that this change already goes a long way in improving the standard definition of the SAC for high-G aircraft.

   Influence on the results: The overall results are not very much affected by this change. The largest difference is in the fitting of the potential persistent contrail formation as a function of the mixing line slope G (Figure 7 and Table 2) at high values of G (hydrogen-powered aircraft).
2. **Overall propulsion system efficiency of reference aircraft**
   We received a comment from a colleague that our initial choice of overall propulsion system efficiency for the reference aircraft CON-LG ($\eta =$ 0.30) is low compared to the current state-of-the-art. This slightly affected the reported percentage increases/decreases of different technologies compared to conventional aircraft. We have, therefore, decided to use a state-of-the-art overall propulsion system efficiency of 0.37 as our reference aircraft (CON-37). We have also tried to always state the reference aircraft when reporting percentage increases/decreases.

Influence on the results: The overall results are not affected by this change, only how they are presented. As a result of increasing the overall propulsion system efficiency, the increase in p_{pcf} due to more efficient engines is slightly reduced. The reduction in the globally-averaged p_{pcf} increase from hydrogen-powered aircraft is mostly due to the change made to the definition of T_{max} (see above), but is also influenced by the change in reference aircraft.

We hope that we have properly understood all comments and feedback and welcome any further comments, suggestions or points of clarification.

Responses to Reviewer #2

Comment R2.1

The study by Megill & Grewe examines the limiting factors related to aircraft design and environmental conditions in the formation of persistent condensation trails. The aircraft design factors considered include propulsion efficiency in relation to the type of fuel used (Sustainable Aviation Fuels - SAFs, hydrogen - H_2 fuel cells and combustion, hybrid electric aircraft, and the Water-Enhanced Turbofan - WET). The environmental conditions studied are ice supersaturation, droplet formation, and droplet freezing. The dataset used to calculate the environmental conditions is the ERA5 data set. The analysis is performed in a 3D dimensional framework using data from the decade of 2010. To limit computation cost and autocorrelation, the authors randomly selected data from a certain number of hours per season. The authors developed climatological relationships describing potential persistent contrail formation as a function of pressure level and Schmidt-Appleman mixing line slope G, and found that the influence of aircraft design on persistent contrail formation decreases with increasing altitude. They found that ice supersaturation is the most limiting factor for all aircraft designs considered. They also found that, on the one hand, globally averaged persistent contrail formation could increase by 13.8% for next-generation conventional aircraft, or by 71.4% if all aircraft were replaced with hydrogen combustion or fuel cell equivalents. On the other hand, water vapor extraction technologies, such as the Water Enhanced Turbofan concept, have the potential to reduce persistent contrail formation by 53.6% to 85.6%.

This is an excellent study, carefully produced and well-written. It fits perfectly within the CPA framework. I therefore recommend publication of this article once the authors have responded to the major and minor comments listed below.

Response to R2.1: Thank you for taking the time to help us improve our manuscript. Your comments are greatly appreciated.

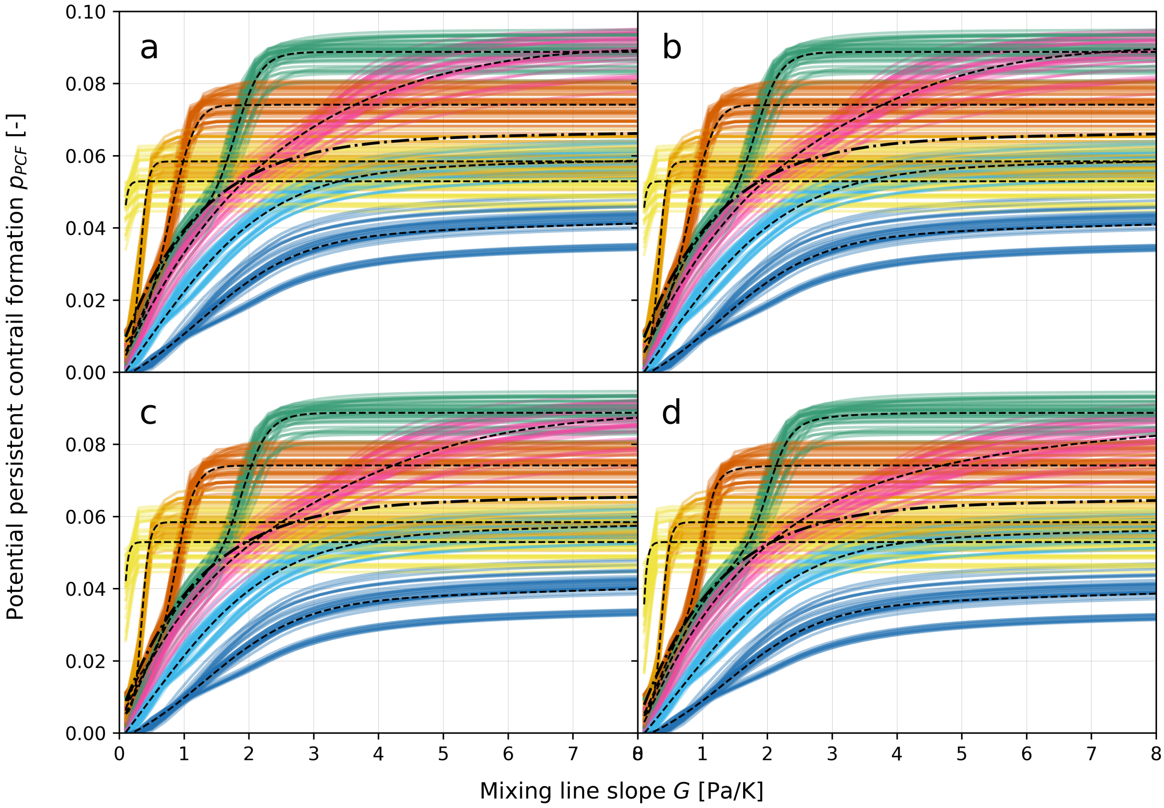
Major Comment R2.2

The authors investigate the limiting factors related to aircraft design and environmental conditions in the formation of persistent contrails using ERA5 data. Consistent with a previous study that reported biases in ERA5 relative humidity, the authors apply a bias correction approach to address this deficiency. However, previous studies have also reported biases in ERA5 temperature data (e.g. Wolf et al. 2023), in the upper troposphere and lower stratosphere. Since temperature is an essential parameter in the Schmidt-Appleman criterion, I recommend that the authors discuss the potential impact of these biases on their results, since they didn't correct them as in Wolf et al. (2023).

Response to R2.2: Thank you for this comment. We are aware of two previous studies that investigated the difference in ambient temperatures between ERA5 and IAGOS: Wolf et al. (2025) - the now published version of Wolf et al. (2023) - and Hildebrandt (2024). From the probability density function in Wolf et al. (2025), for example their Figure 3, we can see that ERA5 both under- and over-estimates the temperature, depending on the pressure level. For the pressure levels 250 - 200 hPa, the average difference is between -0.1 and -0.7 K, meaning that ERA5 on average underestimates the temperature in comparison to IAGOS data. Their Appendix C further shows that there is little dependence of the temperature difference on latitude and longitude. As the altitude increases (pressure level reduces), ERA5 underestimates the temperature more.

We did not initially investigate any corrections to the temperature, because we assumed that this bias would not play a big role in the results. However, following this comment, we introduced a temperature correction and re-ran the climatological potential persistent contrail formation study. We used a global increase in ERA5 temperatures of 0.1, 0.5 and 1.0 K. We are not aware of previous studies that have employed a simple global increase in temperature and note that this is a major simplification. Nevertheless, it should provide an order of magnitude understanding of what effect the bias could have on the results.

We show the results in the figure below (now also in the supplement as Figure S7) - **(a)** uncorrected, **(b)** 0.1 K increase, **(c)** 0.5 K increase and **(d)** 1.0 K increase. We find that the effect of the temperature bias is significantly lower than that of relative humidity. There is very little discernible visual difference between the uncorrected and corrected results. Most notable is the slight reduction in p_{pcf} at 250 hPa (pink).



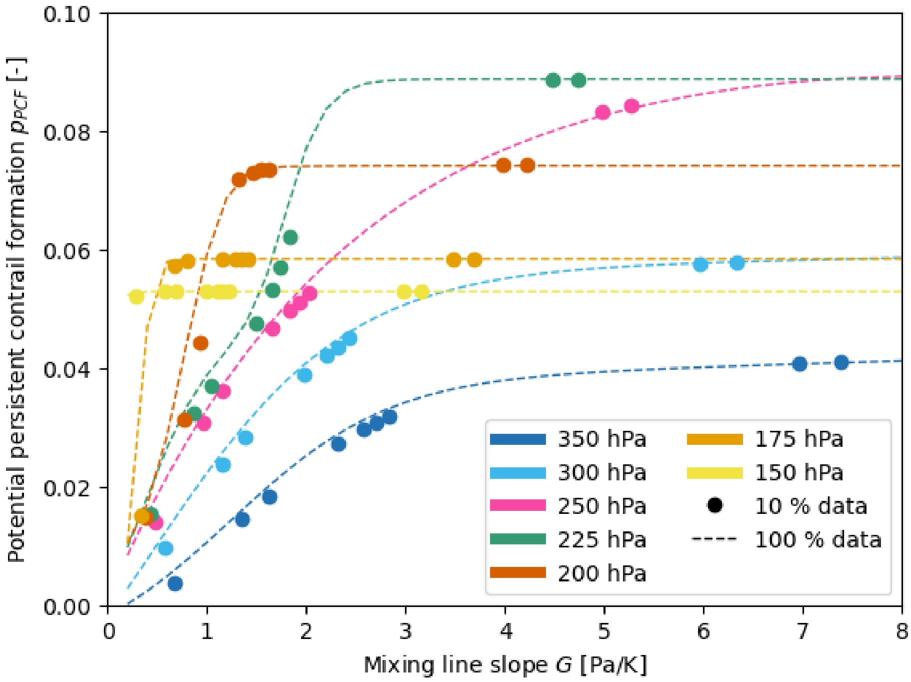
Due to limited computational resources, we are unable to re-run the full limiting factors study with temperature corrections. If there is an effect, it will likely influence the droplet formation limiting factor at pressure levels higher than 225 hPa (altitudes below FL360). However, given the small change to the above response, we assume that the effect to the limiting factors study would also be minimal. We have included a paragraph on ambient temperature corrections in Section 2.4 (ln. 218-224).

Major Comment R2.3

The authors conducted their study over the decade of 2010. To limit computational costs and reduce autocorrelation, they randomly selected 10 % (one-year duration data) of the total data. It is questionable whether the study can be considered a climatological framework study, especially at the regional scale, where the limited number of sampling points may raise concerns about statistical robustness. The authors should perform a sensitivity test on the sample size (number of hours or percentage) to assess the robustness of the results (e.g., variation in the fraction of persistent contrails with fuel change) and the conclusions of the study.

Response to R2.3: For the limiting factors study, we use 10% of all hours within the 2010 decade. On average, therefore, we consider full global data every 10 hours, which we believe is more than sufficient for a climatological study.

We have performed a further analysis to ensure that this is indeed the case. Since the climatological response functions (Figure 7) are significantly less computationally intensive, they are based on *all* hours within the 2010 decade. therefore, we can plot the potential persistent contrail formation for each aircraft in the limiting factors study, using 10% of the data, on top of the fitted responses in Figure 7 - see the figure below. Showing all seasonal values would be too cluttered for this analysis.



We can clearly see that the results using only 10% of the data (circular markers) closely resemble the full results (dashed lines). We also note that the dashed lines correspond to the fits (not the average) and thus a difference can be expected. We therefore believe that 10% of the data is sufficient for a climatological study.

Comment R2.4

L18: Even if persistent contrails quickly dissipate, they can still be expected to have localized and short-term small impacts on the climate. It is preferable to use terms like "small" or "negligible impact", etc. instead of suggesting "no impact."

Response to R2.4: This is a good point, thanks for raising it. We have updated the wording to include "negligible impact" as suggested.

Comment R2.5

L18: Please start a new sentence from “In certain conditions”

Response to R2.5: We have split the sentence as suggested into two: "Most contrails quickly dissipate and have a negligible impact on the climate. However, in certain ambient conditions, contrails can spread to form contrail-cirrus clouds and persist for many hours (Haywood et al., 2009; Schumann and Heymsfield, 2017)." (ln. 18-20).

Comment R2.6

L22: Please, cite the references in chronological order and ensure this is consistently applied throughout the manuscript.

Response to R2.6: We have modified the order of the references as suggested.

Comment R2.7

L205: Please specify what RHi_C is.

Response to R2.7: We did indeed not specify what this factor is, thank you for pointing this out. We have renamed RHi_C to RHi_{cor} and described it as a "correcting factor" (ln. 212). We believe it should now be clear that this factor is used to correct the relative humidity with respect to ice.

Comment R2.8

L289-90: Please split the sentences into two for easier understanding, starting the second sentence for example with "but in total prevents".

Response to R2.8: We have split the sentences into two as suggested.

Comment R2.9

L95: Please define the acronym ERA5

Response to R2.9: Amended as suggested.

Comment R2.10

L240 : Typos, please change the second "that" before the word “factor” to "the".

Response to R2.10: Thanks for this comment. The first "that" is a conjunction; the second "that" refers to the "given limiting factor", i.e. a specific limiting factor. We believe that this is clearer than using "the".

References

Bier, A., Unterstrasser, S., and Vancassel, X.: Box model trajectory studies of contrail formation using a particle-based cloud microphysics scheme, Atmos. Chem. Phys., 22, 823–845, https://doi.org/10.5194/acp-22-823-2022, 2022.

Bier, A., Unterstrasser, S., Zink, J., Hillenbrand, D., Jurkat-Witschas, T., and Lottermoser, A.: Contrail formation on ambient aerosol particles for aircraft with hydrogen combustion: a box model trajectory study, Atmos. Chem. Phys., 24, 2319–2344, https://doi.org/10.5194/acp-24-2319-2024, 2024.

Haywood, J. M., Allan, R. P., Bornemann, J., Forster, P. M., Francis, P. N., Milton, S., Rädel, G., Rap, A., Shine, K. P., and Thorpe, R.: A case study of the radiative forcing of persistent contrails evolving into contrail-induced cirrus, J. Geophys. Res., 114, 2009JD012650, https://doi.org/10.1029/2009JD012650, 2009.

Hildebrandt, K. G.: Ice Supersaturated Regions: Validation of ERA5 Reanalysis with IAGOS In-Situ Measurements and Effect on Contrail Formation Potential of Flights, Delft University of Technology, Delft, NL, 2024.

Schumann, U. and Heymsfield, A. J.: On the Life Cycle of Individual Contrails and Contrail Cirrus, Meteorological Monographs, 58, 3.1-3.24, https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0005.1, 2017.

Wolf, K., Bellouin, N., Boucher, O., Rohs, S., and Li, Y.: Correction of temperature and relative humidity biases in ERA5 by bivariate quantile mapping: Implications for contrail classification, https://doi.org/10.5194/egusphere-2023-2356, 9 November 2023.

Wolf, K., Bellouin, N., Boucher, O., Rohs, S., and Li, Y.: Correction of ERA5 temperature and relative humidity biases by bivariate quantile mapping for contrail formation analysis, Atmos. Chem. Phys., 25, 157–181, https://doi.org/10.5194/acp-25-157-2025, 2025.