“Reduced ice number concentrations in contrails from low aromatic biofuel blends” submitted to Atmospheric Chemistry and Physics by Bräuer et al. 2021

Referee #1 (Comments to Author):

A few preliminary comments on this very well-done article:

Answer to Referee #1:

We would like to thank Andrew Heymsfield for his comments and his motivation to improve the paper. Below we answer the comments of Referee #1.

Comments:

C1: Lines 91, 92: I suggest adding an equation for calculating the extinction coefficient.

A1: We followed the suggestion.

C2: Line 101: relative humidity with respect to ice

A2: We followed the suggestion.

C3: Figure 3: Could you do a plot of the temperature and relative humidity distribution with altitude?

A3: We added the temperature and relative humidity distribution with altitude as subplots to Figure 1. You can find a corresponding plot in Bräuer et al. (2021), which focused on the effects of ambient conditions during ECLIF II/NDMAX on contrail microphysics.

Bräuer, T.; Voigt, C.; Sauer, D.; Kaufmann, S.; Hahn, V.; Scheibe, M.; Schlager, H.; Diskin, G. S.; Nowak, J. B.; DiGangi, J. P.; Huber, F.; Moore, R. H. & Anderson, B. E.: Airborne Measurements of Contrail Ice Properties - Dependence on Temperature and Humidity, *Geophys. Res. Lett.,* 2021

C4: I think it's essential to show particle size distributions-I have some questions about how you extrapolated the FFSSP data to sizes below 1 micron.

A4: Three particle size distributions for different flight altitude ranges can be found in Bräuer et al. (2021). We added a description of the FFSSP data extrapolation between a particle diameter of 0.5 and 1 µm to the manuscript: “The correction is based on the Cloud and Aerosol Spectrometer (CAS), which was also on board the DC-8 during ECLIF II/NDMAX and measures ice particles with diameters between 0.5 and 50 µm. A function was fitted to the ratio between the total CAS number concentration and the CAS number concentration for particles larger than 1 µm. The correction function increases exponentially with decreasing contrail effective diameter (Francis et al., 1994). The FFSSP ice number concentrations are corrected by multiplying them with the size-dependent correction function. The error of the correction increases with decreasing effective diameter.”

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Francis, P. N.; Jones, A.; Saunders, R.; Shine, K.; Slingo, A. & Sun, Z.: An observational and theoretical study of the radiative properties of cirrus: Some results from ICE'89, *Q. J. R. Meteorol.Soc*, 1994, 120, 809-848

Referee #2 (Comments to Author):

As sustainable aviation fuels have been adopted by the airline industry at an increasing rate, this paper addresses a highly relevant and timely topic of their non-CO2 climate impacts. The authors present unique experimental data obtained during elaborate chase studies at cruising altitudes representative of commercial flights. The work presented extends the subset of results shown by Voigt et al. 2021 from the same campaign to higher altitudes and gives more details on the experiments.

Overall, the paper reads well and provides enough background information for nonexperts to understand the results and implications. The title and abstract reflect well the contents of the paper. The methodology and results are well supported with appropriate references.

Answer to Referee #2:

We would like to thank the referee for her/his positive review and interest in the subject of biofuel blends and their effect on contrail formation. Especially the plots and their descriptions were much improved by the referee's suggestions. Below we answer the comments of Referee #2.

General comments:

C1: In the introduction, the authors summarize nicely what we do know about the climate impacts of aviation today. However, it is unclear what is the knowledge gap this paper tries to fill (besides providing more data than the recently published study by Voigt et a.). Perhaps it is obvious to experts in the field, but a general reader might benefit from information on why these kinds of measurements are needed and what data is missing (e.g., for climate impacts modeling?)

A1: We agree with the referee, that we did not explain sufficiently the knowledge gap, which we like to fill with this paper. Therefore, we added the following text to the introduction: " Burkhardt et al. (2018) showed with a global simulation that the climate impact of contrails is non-linearly dependent on apparent ice emission indices. Therefore, we contribute to the assessment of the contrail climate impact by deriving optical parameters like the extinction coefficients and optical depths of young contrails in addition to the apparent ice emission indices."

C2: The authors mention several times that the fuel composition effects on soot emissions (and AEI of ice) depend on the types of aromatics. To account for the effects of different types of aromatics, fuel hydrogen content (or H/C) has been found to be the best (practical) predictor. Data from numerous studies (including data from engine manufacturers) were used to develop a standardized correlation of fuel composition effects with engine thrust setting and fuel hydrogen content, which is now part of the nonvolatile PM emissions certification (see the latest version of the ICAO Annex 16 Vol. II, Appendix 7, section 6.2). Of course, this correction is applicable for ground emissions tests, but it seems that a fuel H (or H/C), based on results in Figure 2, could be used for predicting reductions of contrail impacts.

A2: The latest version of the ICAO Annex 16 to the Convention on International Civil Aviation improved the standards for nvPM mass and number emission index estimation in air. For calculation, the engine exhaust gas temperature and the thrust for the given operating mode is needed. This information is normally only known to the engine manufacturer or can be estimated by strongly simplified performance models. Nevertheless, there are already contrail prediction models which use the soot emission index as input parameter. For example, CoCiP simulates contrail formation on the basis of the Schmidt-Appleman criterium (Schumann, 1996; Schumann, 2012; Teoh et al., 2020). Flight experiments like ECLIF II/NDMAX are needed to validate these models.

Schumann, U.: On conditions for contrail formation from aircraft exhausts, *Meteorol. Zeitschrift,* 1996, 5, 4-23

Schumann, U.: A contrail cirrus prediction model, *Geosci. Model Dev*., 2012, 5, 543–58

Teoh, R.; Schumann, U.; Majumdar, A. & Stettler, M. E. J.: Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption, *Environ. Sci. Technol.,* 2020, 54, 2941-2950

C3: Can it be assumed that the results presented apply to a wide range of aircraft engines with different soot emission characteristics? The engine type measured here has relatively high non-volatile PM emissions compared to other engine types (ICAO emissions databank v 28C). Some of the latest engine types of the same size (should) emit up to 5 orders of magnitude fewer soot particles per kg fuel at medium to high thrust. Assuming similarly low emissions at cruise, would the reduction of soot emissions with SAF still play a role in contrail impacts, or would the sulfur content be more relevant?

A3: The question behind Comment 3 is: How do low soot levels from modern engines change contrail formation? Kärcher (2018) simulated with a microphysical model, that especially for conditions well below the formation threshold temperature and for soot emissions below 10^{14} per kg fuel, ultrafine aqueous particle activation will be enhanced. However, this effect is not yet empirically documented and we cannot answer the question with the dataset of ECLIF II/NDMAX. But our publication shows, that with the individual design of an aircraft fuel, we can reduce contrails significantly and we believe that these findings will stay relevant for modern engine soot levels.

Kärcher, B.: Formation and radiative forcing of contrail cirrus, *Nat. Commun.,* 2018, 9, 1824

Specific comments:

Figures:

C1: Figure 2: The legend should include information about the error bars shown. Do they represent standard deviations of the single plume encounters?

A1: We agree with the referee to include information about the error bars. They show the standard deviations of the single plume encounters.

C2: Figure 2: The dashed lines connecting the means may be somewhat misleading given the low number of data points, suggesting there are linear trends between the means. Consider removing these lines.

A2: We followed the suggestion.

C3: Figure 3: No information about the error bars is provided. Only a subset of points includes error bars. Do the points without error bars represent single observations?

A3: We agree with the referee to include information about the error bars. They show the standard deviations of the single plume encounters in the 30 m (60 m) sections. For clarity and better readability, only a subset of the error bars is shown in the figure.

C4: Figure 3: In panel c, the error bars are "sticking out" of the panel. Consider changing the range of the x-axis or pushing the error bar back.

A4: We followed the suggestion.

C5: Figure 3: The purpose of the shaded areas is not clear to me. Is it just to distinguish between panels a and b? If that is the case, perhaps using open symbols might work visually better.

A5: As explained in the text: “The ECLIF II/NDMAX CODs for the measured fuels are calculated by integration of the extinction coefficients shown in Figure 3c and d (shaded areas).” We added a sentence to the description of Figure 3.

C6: Figure 3: The horizontal reference line at 0 m is barely visible in the pdf and invisible in a printout. Perhaps you could increase the line thickness.

A6: We followed the suggestion.

C7: Figure 4: There is no description in the legend of what we see in panels a and b. Perhaps a sentence similar to the description in the text (line 132-133) could be included.

A7: We followed the suggestion.

C8: Figure 5: One more comment on the missing description of the error bars (sorry). In the text (line 160), you mention that variability bars (error bars?) "reflect the uncertainties in the physical depths of the contrails". How were these calculated?

A8: We agree with the referee to include information about the error bars (thanks again). The COD are calculated in dependence of the physical depths of the contrails. We added the text: “The bars show the COD range for the uncertainty in physical contrail depths and are estimated based on the distribution of the measurements over the vertical range of the contrails.”

Tables:

C1: Table 1: In the comment for the fuel Ref 4, you could replace the word "probed" with "used" if that is what you meant.

A1: We followed the suggestion.

Text:

C1: Line 35: The study by Beyersdorf et al. was done on an old aircraft type (the DC-8 used in your study) and actually proved that it could not operate for a long time with 100% SAF (leaks in the fuel system due to the absence of aromatic compounds). Consider rephrasing or deleting.

A1: We followed the suggestion.

C2: Line 36: even higher reductions could be reached with higher blending ratios and old engine technology (see Tran et al. 2020 https://pubs.acs.org/doi/10.1021/acs.energyfuels.0c00260)

A2: We added the citation of Moore et al. (2015) and Tran et al. (2020).

C3: Line 103: You write the AEIs are independent of thrust level. The soot EIs depend on engine performance (which depends on aircraft speed, weight, altitude, delta T from ISA, etc.). Therefore, aren't the AEIs of ice also dependent on engine performance (thrust level)?

A3: We agree with the referee that soot and apparent ice emissions are not proportional to fuel burn and we deleted “thrust level”.

C4: Line 152: "In a next step...in the following section." This sounds repetitive. Consider rephrasing

A4: We followed the suggestion.

C5: Line 203: The very last statement about hydrogen fuels seems irrelevant and not supported by the results. Consider deleting.

A5: We followed the suggestion.