Comments I (italicized), and responses (blue):

Any shift in estimates of effective radius forcing of aviation CO2 and non-CO2 emissions has important repercussions for assessing the trade-offs between the long-lived (CO2) and short-lived (contrail cirrus, for that matter) forcing agents [Simpkins, 2020]. This study is an important stepping stone towards research into the global climate effects of in-cirrus contrail formation, a hitherto under-researched aspect of contrail formation.

The authors focus on the contrail formation stage and modify an existing contrail parameterization scheme [Kärcher et al., 2015] to account for in-cirrus contrail ice formation by enhancing the water vapor emission index consistent with adding cirrus ice water sublimated within aircraft engines/combustors. Changes in the water vapor emission index as input to the original parameterization should lead to robust results regarding changes of the contrail formation threshold temperature.

With regard to the proposed modification, the sublimated cirrus ice water content was added to the mass emission index of water vapor resulting from fuel combustion with an assumed efficiency of 100%, cf. eqs 2+3. It might be appropriate to note that this assumption does not consider vapor losses e.g., on wall surfaces and the effects studied are therefore upper limit estimates.

Moreover, this approach does not capture the possible impact of sublimating cirrus ice crystals entrained into the expanding jet plume prior to and alongside contrail formation. The sublimation of entrained cloud ice in the bypass regions away from the jet core might lead to an increase in the plume water vapor mixing that may be larger than that from ice crystals sucked into the engines, based on microphysical studies of contrail ice formation including entrained cirrus ice [Kärcher et al., 1998]. This increase depends on the ambient cirrus ice crystal number-size distribution and temperature. Ideally, a quick yet reasonably accurate estimate of the contribution of a continuously entrained sublimating cirrus ice crystal population to total plume water vapor may be obtained by applying the flow field model described in Kärcher & Fabian [1994].

'Warm' contrails are those observed at flight levels at temperatures well above those obtained by the standard thermodynamic model [Jensen et al., 1998], i.e. typically above about 225 K. It is possible that they form in high humidity (possibly cloudy) regions. The formation of such contrails might be explainable by one of the above mechanisms associated with in-cirrus contrail formation, or by both.

→Thank you for your comment. We have introduced many changes to our study that consider the reviewer's and your comments.

We do now consider the ice crystals that are mixed into the plume after emission. We estimate the sublimation of the cirrus ice crystals and the deposition that is happening after the plume reaches ice saturation and modify the slope of the mixing line accordingly. We added an appendix describing how we estimate the sublimation/deposition on the cirrus ice crystals mixed into the plume based on the diffusional growth equation. Figures and text were modified throughout the paper.

We estimate that in some instances the impact of the preexisting cirrus ice crystals is to reduce contrail ice nucleation while in most occasions ice crystal nucleation is enhanced. The likelihood of this happening depends on the atmospheric conditions.

To our knowledge the H2O content of the air is not changed when going through the engine. Water does not accumulate in the engine.

We do reference now to the 'warm' contrail estimate in Kärcher et al. 1998.

The authors are aware of the fact that during contrail formation within cirrus, contrail ice crystals get entrained in to jet plumes (line 259f). Consequently, they estimate the sublimation losses that are expected to occur when entrained cirrus ice crystals get captured in downward propagating wake vortices, albeit again with an assumed efficiency of 100%. Equation 5 makes total sense to me, as in the initial phase of sublimation, the total cloud ice crystal number stays constant while the ice water mass is decreasing. However, at some point cloud ice crystal numbers will start to decrease as well, once the smallest ice crystals fully sublimated to their aerosol cores [illustrated in fig S1 in Kärcher & Voigt, 2017]. The point where this happens obviously depends on the mean ice crystal size.

→We changed our representation of the contrail ice crystal loss in the vortex phase to include the ice crystal growth phase after contrail nucleation and before vortex descent. We treat that phase using the full diffusional growth equation which can lead to significantly reduced contrail ice crystal sizes.

It is true that the microphysical two-moment scheme of ICON LEM (without an explicit representation of the size distribution) is one of the reasons for uncertainty in our simulations. But since the impact of pre-existing cirrus ice crystals on the vortex phase loss is very low, this uncertainty should be of limited importance.

Due to their smaller mean size, the contrail variables (total number and mean size) will change much faster during sublimation than the corresponding cirrus variables. I was just wondering whether eq 5 accounts for effects of changing number and size of cirrus and contrails during the sublimation process. If not, how much will the application of eq 5 with constant integral radii for contrail and cirrus ice will deviate from estimates where these variables are allowed to change?

→Our equation 5 is significantly changed now in order to consider the full dependence of diffusional growth on ice crystal sizes. We include now in our estimate of ice crystal loss in the vortex phase the competition of contrail and cirrus ice crystals before vortex descent. We calculate the temporal evolution of both contrail and cirrus ice crystals in order to have a good estimate of ice crystal sizes before the vortex descent. Afterwards we use equation 5 in order to estimate the cirrus ice water that sublimates in the time that it takes the contrail ice crystals to sublimate without updating the ice crystal sizes. Since the changes in the ice crystal survival due to the impact of cirrus ice crystals is very low, we do not think that inclusion of this would have a large effect on the simulations.

References

Simpkins, G. The climate cost of flying Nat. Rev. Earth Environ., 1, https://doi.org/10.1038/s43017-020-00104-0, 2020

Kärcher, B., Burkhardt, U., Bier, A., Bock, L. & Ford, I.J. The microphysical pathway to contrail formation J. Geophys. Res., 120, https://doi.org/10.1002/2015JD023491, 2015

Kärcher, B., Busen, R., Petzold, A., Schröder, F.P. & Schumann, U. Physico-chemistry of aircraft-generated liquid aerosols, soot, and ice particles. 2. Comparison with observations and sensitivity studies J. Geophys. Res., 103, https://doi.org/10.1029/98JD01045, 1998

Jensen, E.J., Toon, O.B., Kinne, S., Sachse, G.W., Anderson, B.E., Chan, K.R., Twohy, C.H., Gandrud, B., Heymsfield, A. & Miake-Lye, R.C. Environmental conditions required for contrail formation and persistence J. Geophys. Res., 103, https://doi.org/10.1029/97JD02808, 1998

Kärcher, B. & Fabian, P. Dynamics of aircraft exhaust plumes in the jet regime Ann. Geophys., 12, https://doi.org/10.1007/s00585-994-0911-9, 1994

Kärcher, B. & Voigt, C. Susceptibility of contrail ice crystal numbers to aircraft soot particle emissions Geophys. Res. Lett., 44, https://doi.org/10.1002/2017GL074949, 2017