We wish first to thank you very much for your important and relevant comments. You will find below an answer to all the comments and the corrections we propose in the paper.

Note: Corrections from your comments are highlighted in blue color in the paper.

GENERAL COMMENTS :

Reviewer comment: *The analysis of the extinction and optical depth of young contrail may be misleading and misinterpreted by readers.*
a.
The contribution of the first few minutes of the full contrail lifecycle to the time-integrated radiative forcing (or extinction) is usually not substantial. A relatively
larger extinction in the beginning does not imply a larger radiative impact at later
times and in total.
Authors answer: Thank you for this valuable comment. We agree that the early contrail radiative forcing is not relevant for the climatic impact of a contrail. And that an initial larger extinction does not imply a larger radiative impact several hours later. In order to avoid misinterpretation the following warning has been added **line 487**:

Indeed, the differences in extinction observed for the first few minutes may potentially decrease, or even vanish, over longer timescales owing to the effect of atmospheric turbulence and wind shear on the ice crystals spatial distribution. A larger extinction in the beginning does not necessarily imply a larger radiative impact at later times and over the full lifetime of the contrail.

Reviewer comment: *Simulations in Unterstrasser & Gierens (2010b) and Lewellen (2014) show that the total number of ice crystals is the most crucial quantity of young contrails that determines the further fate. The early ice crystal mass (and also optical depth and integrated extinction) does not significantly affect the long-term behaviour of the contrail-cirrus transition. Hence, an evaluation of total ice crystal number would be more insightful.*

<u>Authors answer:</u> We give the evolution of averaged ice crystal number (Np) in the contrail as a function of time (Fig.7, Fig. 15, Fig.20 and Fig.24). We believe this gives an insight on the number of ice crystals in the domain.

<u>Reviewer comment</u>: *Moreover, I strongly suggest to not use the term "radiative forcing of young contrails". First of all, radiative forcing is defined as a radiative imbalance typically evaluated at the top of the atmosphere and this is not what is evaluated in your study. You should make clearer, how to interpret the extinction quantity that you analysed.*
<u>Authors answer:</u> "Young contrail" has been replaced by "Recently formed contrail" and "Radiative forcing" (RF) by "extinction" except for the reference to Ferreira et al. work where an RF parametrization has been used to estimate RF for a recently formed contrail. However, it is true that we cannot extrapolate the results of our simulations to estimate RF a few hours after the end of the dissipation phase, that is in the diffusion phase.

<u>Reviewer comment</u>: *In line 515, the conclusion states, e.g., "RANS initialization produced a more turbulent contrail with ... increased radiative impact". I think this formulation is too strong. Similar formulations appear in other locations as well.*
<u>Authors answer:</u> Radiative impact has been replaced by extinction and/or radiative properties. It is true that we cannot deduce radiative impact of recently formed contrails solely from the extinction as extinction takes into account both light scattering and light absorption by the ice crystals.

<u>Reviewer comment</u>: *How robust are the evaluations of* Δz *and* Δ*y? In Eulerian models, contrails typically do not feature very strong gradients at the boundaries and fade out. Hence, the values you determined may depend on thresholds with which you define a contrail. I believe it would help readers to also show vertical and transvers profiles of ice crystal number and mass. This would allow for a more quantitative comparison compared to Figs. 7, 8 and 12 and also makes clearer how robust the evaluations of* Δz *and* Δ*y are.*
<u>Authors answer:</u> Yes, it depends on the treshhold but the goal here was to compare the different initialization strategies results using the same treshhold. Spatially averaged ice crystal numbers field 2D contours have

been added to the paper (Fig.12, Fig.13, Fig.21, Fig.23) to have a better understanding of contrail size.

Reviewer comment: *How is the boundary of the contrail defined? Why do you choose to apply a weighting by number? Why at all and why not by ice mass e.g.? No spatial distributions of ice crystal number concentration are displayed. Nor the time evolution of total ice crystal number is shown. Hence, it is not transparent what effects the weighting in the averaging procedure does introduce.*

Authors answer: The contrail is defined by the mesh cells where the ice crystal radius rp is strictly greater than the radius of a dry soot particle rs (27 nm). This is now stated in the paper. Thus, only particles with an ice cap are considered. Those particles are by definition ice crystals. We applied a weighting by number of ice crystals because it adequately represents the influence of each ice crystals on the contrail mean quantities. For X a microphysical quantity, each value X contributes to the average proportionally to how many particles have that value. This is exactly the same as weighting by the number of ice crystals. Such weighting is commonly used in statistical physics. If we weighted by ice mass, we could have situations where a cell have a high ice mass but not that many ice crystals, which would bias the computed mean.

Reviewer comment: *Your analysis focuses on intensive mean quantities, which depend on the contrail-cross-section of the contrail. It would be interesting to also see integrated quantities like the total ice crystal number and mass (which do not depend on the definition of the contrail boundary).*

Authors answer: We believe that the definition of the contrail boundary by rp>rs is valid enough to define the contrail boundary with no ambiguity. As mentioned in the previous answer, in our model if a particle radius is less or equal to its core soot radius, it is not an ice crystal. Therefore averaging on every cell where rp>rs consider all of the ice crystals in the computational domain.

Reviewer comment: *Your interpretation of the simulation results focuses on the differences in the dynamical setup (RANS versus 2LO and 4LO). It is not much discussed that in addition the exhaust plumes are initialized in a different way. Currently you simply assume that observed differences in the simulation results are due to the different wake* *vortex initialization, but this is not really proven. It may help to perform another type simulation where the RANS with the idealised exhaust plume or the LO wake vortices are combined with the RANS exhaust plume. This way you could answer, which of the two aspects is more crucial.*

Authors answer: We completely agree with this comment. Another simulation with the two Lamb-Oseen vortices but this time with the RANS exhaust plume was performed. The results are shown and discussed in the new section 4.4. It is found that vortex initialization influences the contrail evolution more than plume initialization, at least for the conditions considered in this work.

Reviewer comment: *Why do your simulations run up to t= 200s? Previous contrail vortex phase simulations considered a longer time period (5 minutes or longer). Have the vortices decayed after that time? Both Nb values represent strongly to extremely stable conditions. Air masses that move downwards will rise when the vortices get weaker. Is this process already completed at t=200s? It would be interesting to see whether vertical profiles change more slowly after the vortices break up and buoyancy-driven air motions cease. Is this already the case after 200s? The background of the question is that Fig.8 shows a strong difference after 200s between 'RANS' and '2LO'. It is not clear if this discrepancy is just a transient phenomenon and whether the difference between the two simulations is long-lasting (as the vertical distribution does not change much beyond t=200s).*

Authors answer: The simulations run up to t=200 s because this corresponds approximately to eight characteristic timescales tb for the vortex pair descent. Crow instability (see Crow [1] and Sarpkaya [2] work) destroys the vortex pair between 1 and 8 tb, the exact value depending on the atmospheric turbulence intensity and atmospheric stratification. For our simulations, the vortex pair destruction happens around t=4.5tb for the medium stratification scenario and at t~3tb for the strong stratification scenarios. After the vortex pair destruction, the influence of the aircraft aerodynamic wake begins to decrease. At t=200 s, most of the secondary wake has reached flight altitude and beyond. This statement can be supported by the fact that the contrail height increase is slowing down in the vortex phase, even reaching a plateau for strong stratification case. Therefore, 200 s of simulations is enough to observe and comprehend the impact of the initialization strategy on the LES. Whether the strong difference between "RANS" and "2LO" is a transient phenomenon is an open question. But, considering the shapes of the curves in Fig14, the observed differences are very unlikely to fade out at 300s if it is a transient phenomenon. If it is transient, we believe that we will observe the merging of the curves in the diffusion regime, which is beyond the scope of this study. We believe that the contrail size difference will remain or initially increase with the addition of wind shear but that both contrails might eventually be of comparable size after a few hours, meaning that it could have an influence on its climatic impact.

Reviewer comment: *Line 155: What do you mean with heterogeneous nucleation? The scientific consensus is that contrail formation occurs on condensation nuclei via heterogeneous droplet nucleation, with subsequent homogeneous freezing. Referring to heterogeneous nucleation may imply that soot particles act directly as ice nuclei (IN). In Equation (9), it appears that soot particles are assumed to become ice crystals immediately upon activation. Why is the liquid phase and the freezing process not explicitly represented in your model? Another manuscript in review for ACP by Ponsonby et al. (https://doi.org/10.5194/egusphere-2025-1717) states: "To that end, several LES models prescribe water saturation as the critical condition for contrail ice formation (Paoli et al., 2013; Picot et al., 2015) or heterogeneous ice nucleation as the primary formation pathway (Khou et al., 2017, 2015), both of which have been rejected by in- situ observations (Kärcher et al., 2015). More representative microphysical treatment can be achieved using 0D box- and parcel model simulations (Bier et al., 2022; Rojo et al., 2015; Yu et al., 2024). Here, the dilution of a parcel of exhaust air is simulated and microphysical phase transitions such as particle activation and homogeneous ice nucleation are tracked. While these models are unable to incorporate feedback between different plume parcels, which may otherwise lead to a diversity of particle history(Lewellen, 2020), they are configured for sophisticated treatment of complex ice microphysics, which is critical for describing contrail properties (Yu et al., 2024)."*

Authors answer: By heterogeneous nucleation we mean condensation of water vapor around a nucleation site (soot particles in the case of this study). We agree that the transformation of the liquid water on soot to ice is achieved with homogeneous freezing. We disagree with the mentioned paper on that point, that is Khou et al. [3] model not explicitly solving the freezing as you mentioned it. This hypothesis has been made mostly because of the monodisperse hypothesis, which guarantee that, considering the low ambient temperature, every particles will become ice crystals. If we admit that the microphysical scheme needs some refinement for the ice crystal refinement, once ice crystals are formed, we have the usual condensation/sublimation equation. Therefore, the vortex phase results still yields.

SPECIFIC COMMENTS :

Reviewer comments are in *italic*.

- *Line 2: The accumulated CO_2 emissions by aviation*
→ It has been changed accordingly

- Line 12 : *Make clear that this statement holds only for young contrails. Emphasize that further research for long-lived contrails is needed:*
→ modification in **line 15** where it is emphasized that those results only hold in the first few minutes after ice crystals formation.

- Line 16 : *replace nucleation by condensation:*
→ done

- Line 44 :*The ice crystals do not heat up adiabatically. The surrounding air does so:*
→ adiabatic heating replaced by heating (**line 49**)

- *Line 50: Do those vortex rings always form?*
→ If Crow instability is triggered and is responsible for the vortex pair destruction, vortex rings will form. For strong stratification, other instabilities might destroy the vortex pair before Crow instability. If that occurs, no rings will be formed. This has been clarified in **line 56**.

- Line 52 : *I would prefer to reformulate to something like "Contrail evolution is driven or governed by physical processes (not by conditions) which are affected by (conditions like) wind shear, stratification etc.*

→ Modifications implemented accordingly.

- Line 55 : *Lewellen (2014) is also a great source of contrail-cirrus analyses.:*
→ Yes, it is now cited (**line 62**)

- Line 117 : *to form ice crystals, condensation is not enough, you should explicitly mention also the freezing process. :*
→ Yes, precision added in **line 127**.

- Line 126 : *already stated in line 115:*
→ Yes, the text has been modified accordingly (**line 135** crossed out).

- *Inclusion of Eqs. (7) -(9) into the text would facilitate reading :*
→ We have tried to do so but we found the text easier to read the way it was so we did not change it in the end.

- *Eqs. 2, 3 and 6 do not convey a lot of information. With which rates do those conversions occur? Would it be more informative to write the equations for the mass fractions of all or selected quantities?* :
→ The mass production rates are now given in Eq.2 and Eq.4.

- *Section 3.2 does not explicitly mention how water vapour is initialized. The sentence in line 281 may imply that absolute water vapour mixing ratio is held constant with altitude. Most other studies of the contrail vortex phase kept the relative humidity constant. Could you plot RHi(z) to see how much this quantity changes with altitude? :*
→ Ambient water vapour is initially constant in the computational domain. We decided to keep ambient water vapour constant instead of RH after informal discussions with climate scientist colleagues. ISSR measurements are needed to accurately define RH and water vapour profiles in the tropopause. RH profiles are now given in in Fig. 5 for the two stratification scenarios. With this hypthesis very high values of RH are reached at the bottom of domain in the strong stratification case. However, no ice crystals descend at such altitude. This point has been developed clarified in **line 301**.

- *Fig. 9: the contrail height and width evolution of the RANS case with Nb =0.03 s^-1 looks a bit strange in the sense, that at t=4.5 the height suddenly stops to increase (which might be linked to vortex break up) and width increases. What process leads to such a large change in the width increase?*
→ Height stopping to increase is due to vortex break up which happens sooner for Nb=0,03 s^-1. The width increase is most likely due to the strongly turbulent nature of the secondary wake that will mix the ice crystals with the ambient air way more efficiently. This has been clarified in **line 440**.

- *Section 4.1. It would be interesting to also see the time evolution of total ice crystal number I and mass M and possibly also of the ratio Nice/Ns. M ice and N ice are more straightforward to analyse and interpret than the derived mean radius ~(M ice /N ice) 1/3 . Computing the mean radius via M ice and N ice is probably better than evaluating rp in each grid cell and do a number-weighted average. How much do the computed values differ between the two formulas? The formula in line 325 might be interpreted in a way that rp depends only on IWC. I would prefer to include N ice in the formula*
→ We have added the evolution of total ice mass and total ice crystal number in Fig .9. Concerning the mean ice crystal radius, we are not sure to understand your comment. We believe that knowing the ice crystal radius in each cell of the contrail and doing a weighted average gives a good overview of the ice crystals size in the contrail. rp formula as a function of IWC and N_ice is given in Eq.7.

-*Line 330: If all soot particles are activated and more ice crystals are present, then they should be smaller not larger if ice mass is similar.*
→ This is true but this effect is not taken into account in our Eulerian model. More precisely, our model considers that soot surface activation is done only with sulfur compounds. Ice production term in Eq.4 is directly proportional to activation fraction. Consequently, the higher the activation fraction, the higher the ice production and the higher the ice crystal radius. This represents a limitation of our model, as it should also consider soot activation caused by the ice cap formed on soot particles, and not only activation due to sulfur particles. This point has now been clarified in **line 355**.

- *Line 361: It is not clear, if the scaling of time is applied in the model or only in the presentation of the results. What's the advantage of using a normalized time coordinate in this study? All setups have the same t0 and there is no benefit of normalization to make results better comparable. If you keep the normalized values, it would help the readers to add the t0 value to the figure captions.*
→ The scaling of time is only applied in the results. Normalizing by Crow characteristic time is justified by the fact that vortex pair lifespan (and thus vortex influence on contrails) depends mainly on Crow characteristic time. A medium-range aircraft and long-range aircraft will have a vortex pair lifespan typically between 4 and 8 Crow characteristic times, even though in seconds the lifespan will be very different. However, this distinction is mainly relevant in an aerodynamic context and not necessarily when focusing on ice microphysics. The value of t0 in seconds has now been added to the figure captions."

- *Fig.7. shows soot number density which is not an actual contrail property. Wouldn't it be more logical to show contrail ice crystal number or mass concentration?*
→ Using soot number density is justified as it indicates which parts of the contrail have sublimated and which have reached flight altitude, where ice can form. In the medium stratification scenario, it shows that most soot particles remain without ice at the end of the simulation.

- *Line 374: this sounds like a general statement about contrail formation in strongly stable conditions. But I guess it only relates to your choice of water vapour initialization. Do you mean the actual formation process or the time evolution over 200s?*
→ Yes, the results are only valid for the water vapor mass fraction at flight altitude chosen for this study. We mean time evolution over 200 s because RH is the same at flight altitude for medium and strong stratification scenarios and thus the formation conditions are the same. "Formation" has been replaced by "persistence" in **line 411**.

- *Fig.11: Trends are very similar. Do you expect a long-lasting impact?*
→ That's a good question and we don't really have any clear answer. We can imagine that because of the initial difference in contrail width, wind shear and atmospheric turbulence might maintain the differences.

- *Eq. 19: I believe in the contrail community, the quantity defined in Eq. 19 was first introduced in Unterstrasser & Gierens (2010a) and named total extinction.*
→ It has been cited accordingly.

-*Line 439: Yes, that is the important point. I would appreciate to see this statement also in the abstract.*
→ This has been added in the abstract in **line 16**.

- *Line 504: The statement is too strong for reasons stated above.*
→ The LES simulation with the two Lamb-Oseen vortices and the RANS plume still shows that vortex initialization has a greater impact than plume initialization. For the flight regime studied, initializing the LES with four vortices is more critical that initializing the LES with the more complex RANS plume. However, it is important to note the strength of the short-wave instability will depend on the circulation ratio between the circulation of the main wing-tip vortex and the circulation of the horizontal tailplane vortex (ratio that will depend on the aircraft trim), and the ratio of the distances between the vortices center and the symmetry plane [4]. The importance of plume initialization might be greater for other flight conditions.

TECHNICAL CORRECTIONS :

- *Figure 1: replace M infty by U infty*
→ We disagree, aircraft speed in cruise flight is commonly given in Mach number.

- *Line 21: estimation of effective radiative ERF of contrails and other forcing agents.*
→ Correction added.

- *Line 24: Is controversial the correct word here? What fact is controversial?*
→ We replaced controversial with « currently debated » (see **line 29)**.

- *Lines 103 and 195: "negelected before" does not sound like proper English*
→ « neglected before » replaced by « neglected in comparison to»

- *Line 114 “water vapour H2O” = “gas-phase H20”? Similary, ice-phase H20 s*
→ This has been clarified in **line 122**.

- *Line 155: Contrail (without ‘s’) ice*
→ Correction added

- *Section 3.2 should state the time period that is simulated.*
→ Time period added in **line 272**.

- *Line 301: weighted*
→ Correction added

- *Line 330: soot PARTICLES*
→ Correction added

- *Figure 5 and Figure 10: soot number density is named Ns and Np . Please be consistent.*
→ You are right. Ns is soot number density and Np is ice crystal number and they are not exactly the same quantity. Np is equal to Ns but only in the mesh cells which contains ice, that is when rp is strictly greater than rs. This has been clarified in the paper in **line 420**. Actually, it is the ice crystal number that is plotted in Fig.7.a and not the soot number density since we only consider the cells very particle radius is strictly greater than soot dry particle radius. This has been corrected in the paper.

- *Figure 7: The rp values on the colour bar should have nice values. Is a linear or logarithmic scale used?*
→ The values are now nicer and it has been clarified in the figure caption that a logarithmic scale is used.

- *Line 378 Widnall*
→ Correction added

- *Line 382: length scales*
→ Correction added

- *Line 395: descend*

→ Correction added

- *Line 395: ‘contrail surface reduction’: do you mean a decrease of the contrail cross-sectional area?*
→ Yes. It has been clarified in the text in **line 438**.

References :

[1] Crow, S. C., & Bate Jr, E. R. (1976). Lifespan of trailing vortices in a turbulent atmosphere. *Journal of Aircraft*, *13*(7), 476-482.
[2] Sarpkaya, T. (1998). Decay of wake vortices of large aircraft. *AIAA journal*, *36*(9), 1671-1679.
[3] Khou, J. C., Ghedhaifi, W., Vancassel, X., & Garnier, F. (2015). Spatial simulation of contrail formation in near-field of commercial aircraft. *Journal of Aircraft*, *52*(6), 1927-1938.
[4] Fabre, D., Jacquin, L., & Loof, A. (2002). Optimal perturbations in a four-vortex aircraft wake in counter-rotating configuration. *Journal of Fluid Mechanics*, *451*, 319-328.