Response to Reviewer Comments

We thank the referees for reviewing the revised manuscript. Their additional comments further improved the quality, clarity, and narrative of this manuscript.

The reviewer's remarks are *italicized*, while our responses are presented in normal text. Blue text is used to cite passages from the manuscript and to track the changes made from the original to the revised manuscript. References cited in the blue text can be found in the revised manuscript. Line numbers refer to the clean version of the revised manuscript.

REFEREE 1 (RC1)

In my first review I said that it is necessary to test the radiation parameterisation that is used in the CoCiP and pycontrail. It is good that the authors took that comment seriously. However, I still have a minor comment to their reply.

They write: "We acknowledge your concerns about potential overfitting and the lack of testing against independent profiles. These issues can be captured within the Monte Carlo simulation framework, for example, using the approach of a recent study which evaluated the EFcontrail uncertainties resulting from the parametric RF model and other sources....."

I think that the potential problem of overfitting cannot be captured with a simple MC exercise. In a MC study you would just perturb the parameters a bit and you would get some kind of error bars for each data point. But a fitted noise peak would still be a fitted noise peak embellished with an error bar. This does not help. I think it is really necessary to take an independent set of atmospheric profiles, run Libradtran on it and compare the result with the result of the parameterization. The profiles should contain weak and strong contrails, cooling and warming ones, in order to test whether the residuals are actually independent on contrail RF'.

I would still like to see such a comment in the paper, ideally somewhere in the end where usually some outlook for future research requirements are given.

- Thank you for this feedback. The parametric radiative forcing model developed in Schumann et al. (2012) was formulated using a diverse set of independent atmospheric profiles from libRadTran tested against an independent validation set (excerpts from Schumann et al. (2012) below).
    - "*To cover the variability of contrail RF with respect to contrail and ambient conditions, the dataset includes 4572 different atmosphere-surface cases for each of eight habit types. As sketched in Fig. 1, the cases represent different temperature and humidity profiles, over land and ocean, with and without upper-troposphere ice clouds and lower-level water clouds.*"
    - "*For each case, 22 properties are varied randomly in certain ranges; 50% of all cases include a layer of water clouds, and 50% include a layer of ice clouds; 25% are cloud free, and 25% contain both water and ice clouds.*"
    - "*In total, the dataset contains 36,576 libRadtran cases with data for SW and LW RF.*"
    - "*On average over all habits, the relative errors are 7.1% for LW and 10.6% for SW fluxes. The robustness of the fit has been investigated by repeating the fit calculations with subsets of the test dataset.*"

- While the libRadtran dataset used to train the CoCiP parameterization is extensive, we acknowledge that residual overfitting could still be an issue, particularly for out-of-sample profiles.
- We have made minor revisions to the paragraph on future research requirements. In particular, we have kept our discussion of uncertainty sources broad, noting that uncertainties in the parametric RF model are just one of the many factors that impact the $EF_{contrail}$ estimates. Some uncertainty sources, such as the global humidity corrections, may have a more substantial impact and can change the $EF_{contrail}$ estimates by a factor of two (Teoh et al., 2024). We have also incorporated the reviewer's feedback by refraining from prescribing specific methodologies for evaluating and addressing uncertainties (e.g., Monte Carlo simulation), recognising that further research is necessary to determine the most appropriate approaches:
    - [Main text: Lines 565 – 567] "Future versions of the grid-based CoCiP are also expected to be prioritised towards: (i) **evaluating and** accounting for different uncertainty sources ~~within the Monte Carlo contrail simulation framework~~ **to produce a more comprehensive probabilistic forecast** (Platt et al., 2024);"

REFEREE 2 (RC2)

I thank the authors for their efforts in addressing the review comments so exhaustively. The addition of Appendix A and figures A5-A7 are very useful. Replies to reviewers are very clear and complete, which helped a lot in my assessment of the revisions.

I find that the review comments have been addressed very satisfactorily. I only have a few points where I feel additional statements or guidance would be useful.

1. *Abstract: My request to better highlight the differences between CoCiP and CoCiPGrid was really referring to the difference in their predicted energy forcing, i.e. there is a need to summarise the conclusions of Section 4. Perhaps that could be added after the sentence ending in line 17?*
    - Thank you for the clarification. We have revised the abstract to incorporate this feedback and have shortened some sentences to ensure the abstract stays below 300 words:
        - [Main text: Lines 8 – 24] "The global annual mean contrail **climate** ~~net radiative~~ forcing may exceed that of aviation's cumulative CO_2 emissions ~~by at least two-fold~~. As only ~~around~~ 2-3% of all flights are likely responsible for 80% of the global annual contrail energy forcing ($EF_{contrail}$), re-routing these flights could reduce the **occurrence** ~~formation~~ of strongly warming contrails. Here, we develop a contrail forecasting tool that produces global maps of persistent contrail formation and their ~~associated~~ $EF_{contrail}$, **formatted to align with standard weather and turbulence forecasts for integration into existing flight planning and air traffic management workflows**. This is achieved by extending the existing trajectory-based contrail cirrus prediction model (CoCiP), which simulate contrails formed along ~~provided~~ flight paths, to a grid-based approach that initialises an infinitesimal contrail segment at each point in a 4D spatiotemporal grid and tracks them until their end-of-life. Outputs are provided for ***N* number of**

~~different~~ aircraft-engine groups, **with groupings based on similarities in aircraft mass and engine particle number emissions: *N* = 7 results in a 3% mean error between the trajectory- and grid-based CoCiP; while *N* = 3 facilitates operational simplicity but increases the mean error to 13%** ~~and formatted to align with standard weather and turbulence forecasts, facilitating their integration into existing flight planning and air traffic management workflows~~. We use the grid-based CoCiP to simulate ~~conduct a global~~ contrail**s** **globally using** ~~simulation for~~ 2019 **meteorology** and compare **its forecast patterns** ~~the spatial trends of strongly warming and cooling contrails~~ with **those from** previous studies. Two approaches are proposed **to apply these forecasts** for ~~integrating~~ contrail **mitigation** ~~forecasts into flight planning and air traffic management systems~~: (i) monetising the $EF_{contrail}$ and including it as an additional cost parameter within a flight trajectory optimizer; or (ii) constructing polygons to avoid airspace volumes with strongly-warming contrails. We also demonstrate a probabilistic formulation of the grid-based CoCiP by running it with ensemble meteorology and excluding grid cells with significant uncertainties in the simulated $EF_{contrail}$. This study establishes a working standard for incorporating contrail mitigation into flight management protocols and demonstrates how forecasting uncertainty can be incorporated to minimize unintended consequences associated with increased CO_2 emissions **from re-routes** ~~of avoidance~~."

2. *Lines 55 and 560: The meaning of "second-order" is ambiguous here. Feedbacks are not second order in terms of magnitude (the ERF-to-RF ranges from 0.2 to 0.6) so I guess the authors meant "ensuing" or "subsequent"?*

   - Thank you. We have revised the affected sentences to improve their clarity (see below). Additionally, we also made clear that the effective radiative forcing (ERF) metric only accounts for the rapid atmospheric adjustments directly caused by the contrail (Bickel et al., 2019):

     - [Main text: Lines 51 – 58] "Various physics-based modelling approaches have been employed for this purpose, including: (i) large-eddy simulations (LES) (Lewellen, 2014; Lewellen et al., 2014; Unterstrasser, 2016); (ii) parameterised Lagrangian models such as the Contrail Cirrus Prediction Model (CoCiP) (Schumann, 2012), Contrail Evolution and Radiation Model (CERM) (Caiazzo et al., 2017), and Aircraft Plume Chemistry, Emissions, and Microphysics Model (APCEMM) (Fritz et al., 2020); and (iii) general circulation models (GCMs) which simulate the interaction between contrails and ~~different~~ atmospheric processes, including ~~second-order feedback mechanisms~~ **the rapid atmospheric adjustments directly caused by the contrail, such as changes in water vapor concentration, temperature lapse rate, and natural cirrus properties** (**Bickel et al., 2019;** Bier and Burkhardt, 2022; Chen and Gettelman, 2013; Grewe et al., 2014; Ponater et al., 2021)."

     - [Main text: Lines 562 – 565] "While multiplying the $EF_{contrail}$ by the ERF/RF ratio, c.f., Eq. (8), was used in this study to ~~provide a highly~~ approximate **and account for the rapid atmospheric adjustments directly caused by the contrail (Bickel et al., 2019)** ~~estimate of second-order and longer-term~~

~~climate feedback~~, our future work aims to establish a stronger connection between this computationally efficient $EF_{contrail}$ calculation and the more rigorous CCF calculations (Frömming et al., 2021)."

3. *Line 124: Liquid clouds located under contrails will also affect the RSR and OLR simulated by ERA5 or other meteorological datasets. So aren't their modulating radiative effects also accounted for indirectly?*

    - Thank you for this feedback. Yes, the term "natural cirrus" previously used in this paragraph was intended to account for various cloud types, including both ice and liquid clouds. We have revised the paragraph to better reflect this and improve its clarity:

        - [Main text: Lines 123 – 129] "A parametric RF model, which is fitted to the libRadtran radiative transfer package (Mayer and Kylling, 2005), ~~is used to~~ estimate**s** the local contrail SW and LW RF (RF', the change in radiative flux over the contrail coverage area) at each time step (Schumann et al., 2012a). These RF' estimates indirectly account for ~~natural cirrus~~ **the presence of various cloud types (e.g., ice, liquid, and mixed-phased clouds)** above and below the contrail through input meteorolog**ical**~~y~~ parameters ~~including~~ **such as** the reflected solar radiation (RSR), outgoing longwave radiation (OLR), **effective albedo (i.e., the fraction of incoming solar radiation reflected by the surface and/or clouds),** and the ~~overlying natural cirrus~~ optical depth **of overlying cirrus clouds** (τ_{cirrus}) (Schumann et al., 2012a)."

4. *Line 677: I am not sure I would call a 17% change in globally averaged contrail cover a "minor change". Especially when noting that is associated with a 24% in the magnitude of contrail energy forcing – that alone would influence the economics described in Section 5.2.1 quite a bit. Although time step may not be as strong a source of error as humidity, it seems to be at least a more easily avoidable source of error. So could guidance be clearly given to users that they should use the shortest timestep possible?*

    - Thank you for this suggestion. We have made the following changes in the revised manuscript to address this comment:

        - [Main text: Lines 666 – 671] "Figure A3 shows that the **magnitude and variance of** ~~simulated~~ $EF_{contrail}$ tends to increase as d*t* decreases, with the mean $EF_{contrail}$ per flight distance simulated from a 1-minute d*t* being approximately 24% larger than those simulated from a 30-minute d*t*. **Likewise, the global airspace area forecast with strongly warming contrails ($EF_{contrail}$ > 80th percentile) is 20% larger at a 1-minute d*t* compared to a 30-minute d*t* (1.60% vs. 1.33%, as shown in Fig. A4).** The smaller $EF_{contrail}$ **and coverage area** at larger d*t* values, such as 30-minutes, can be explained by the contrail lifetime ending prematurely."

        - [Main text: Lines 680 – 686] "In this study, we chose a 5-minute d*t* to align with Teoh et al. (2024a), as their $EF_{contrail}$ thresholds (i.e., > 80th and 95th percentiles) were used to identify regions that **are** forecasted to produce strongly warming contrails. ~~For our research objectives, we note that the~~

~~choice of d*t* only leads to minor differences in the regions identified with strongly warming contrails (Fig. A4).~~ While time step error is one of the many sources of errors influencing $EF_{contrail}$, our analysis **in this section suggests** ~~shows~~ that it is not the most dominant one especially when compared to the impact of humidity corrections applied to the ERA5 HRES (Teoh et al., 2024a). **Since d*t* is a model parameter, we recommend that users select a d*t* of 1 or 5 minutes to minimise its impact as a source of error, as smaller d*t* values are expected to result in convergence of the global airspace area forecast with strongly warming contrails (1.60% for a 1-minute d*t* vs. 1.58% for a 5-minute d*t*, as shown in Fig. A4).**"

Technical comments

5. Line 676: "that forecasted" -> that are forecasted

- Thank you. The identified error has been addressed:
    - [Main text: Lines 680 – 681] "In this study, we chose a 5-minute d*t* to align with Teoh et al. (2024a), as their $EF_{contrail}$ thresholds (i.e., > 80^{th} and 95^{th} percentiles) were used to identify regions that **are** forecasted to produce strongly warming contrails."

REFERENCES

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