Reply to comments by Referee #1.

Subsequently, the Referee's comments are repeated in blue color. Our replies follow in black.

We thank the Referee for his (or her) careful review. We respond to the recommendations by extra analyses and by added discussions as explained below.

Summary

The authors use a contrail model to quantify the change in contrail cover over Europe between 2019 and 2020, and the sensitivity of simulated contrail coverage to different modeling assumptions. They find that contrail coverage over Europe fell substantially over Europe during 2020, but that the overall change in net RF was smaller than the change in total flight distance. They gain some insight into the root cause of this through a counterfactual analysis, using mismatched weather and traffic data to quantify the role that meteorological variability had in the difference. They also find that implementation of new contrail interaction terms could reduce the simulated net radiative forcing due to contrails by up to 65% - an intriguing result.

We agree.

The central question of the manuscript is the degree to which contrail coverage over Europe declined between 2019 and 2020, and whether this was proportional to the reduction in flight distance. This question is interesting, but without comparisons to observations its accuracy cannot be evaluated. The authors tease such a comparison but defer it entirely to a second paper.

The second paper, comparing the model results with satellite observations, just got accepted for publication (not yet online). We will refer to this in the discussions when submitting the revised version of this paper.

Schumann, U., L. Bugliaro, A. Dörnbrack, R. Baumann, and C. Voigt (2021). Aviation contrail cirrus and radiative forcing over Europe during six months of COVID-19. *Geophys. Res. Lett., to appear.*

Ideally one should have accurate and representative observations which allow to assess the accuracy of the model predictions. However, when we started this study, such observations were not available. Even now, with some recent observations, the accuracy of model predictions can only be estimated because the observations have their own limitations.

In the absence of observations, it is common practice to present the results from model variants and from parameter studies to get some insight into the possible range of model results. The study shows that the range of model results is large so that a final estimate of contrail effects requires a careful combination of model and observation results.

The authors are also unable to address the question of why this mismatch was present, beyond showing that weather variability alone is not sufficient to explain it. As such, while the data do support the conclusions, and the

methods are appropriate for the relatively narrow scope of the question, the paper constitutes only an incremental advance. In addition, roughly half of the results section is taken up with discussion of methodological advances which seem to have little to do with the central question of the paper.
Overall, it is useful to have the first data point for the likely change in contrail coverage resulting from air traffic reductions in 2020, and the technical advances made in the CoCiP model are significant.

However, the paper would be substantially improved by the inclusion of a comparison to observations, and by either moving the discussion of methodological advances into a separate paper or refocusing their analysis on the central question of the paper. The former in particular would raise the scientific significance of the paper and make the title more appropriate.

We thank the reviewer for this supportive comment. The more critical parts will be reflected in the discussion as also provided below.

Major comments

The overall goal of the paper seems confused. From the abstract alone, two separate objectives are clear: to quantify the change in contrail cover during 2020 compared to 2019 (lines 15-26), and to determine the sensitivity of the CoCiP model to certain model parameters (lines 26-32). Similarly, I count roughly four pages of discussion of the differences in simulated contrails between 2019 and 2020, and around the same number of pages of discussion of the effect of model parameters on simulated coverage. The problem is that these two disparate components do not add up to a complete study, in part because there seems to be little meaningful overlap between the two. Given that the title of the paper is specifically focused on the effect of COVID-19 on air traffic and contrail coverage, my recommendation would be to focus the discussion in section 5 on the question of whether these model advances affect the conclusions of the paper, rather than the current more abstract discussion of the effect they have on individual years.

We agree that this study cannot yet cover all aspects of the complex problem. Further studies are to come. This is reflected in the text and the outlook and will be stressed in the revision.

Specifically, to what degree does each of these model advances change the effect that changes in air traffic had on contrail coverage in 2020 compared to 2019? As it stands, the discussion in section 5 almost exclusively discusses what each of these advances does to the estimated contrail coverage for one year at a time without covering the implications for our understanding of the changes between 2019 and 2020.

The model changes show indeed quantitative differences. However, the qualitative results are unchanged by the parameters varied. This will be stressed in the paper.

Such an analysis would also illuminate the most important observation in the paper, which is (lines 319-321) that the reduction in the net RF was smaller than the reduction in traffic. Currently, the only explanation offered is that “[t]his is due, in part, to different changes of SW and LW RF and to the nonlinear effects from contrail-background humidity exchanges and contrail-contrail overlap”. The paper would benefit from a rearrangement of the analysis to focus on why the traffic, coverage, and RF changes were not all proportional. While this is partially addressed in the paper, the message of which factors contribute what (other than the separation of meteorological factors) is not communicated clearly.

For applications it is certainly important to note that the net RF may change different from the SW and LW parts. However, this should not be surprising. The SW and LW RF values have opposing sign and the SW and LW magnitudes are about a factor of 4 to 6 larger than the net RF magnitude. Hence, small changes in the RF components have large impact on the net RF. We note that the SW and LW RF components depend both on the contrail cirrus optical depth, and are correlated, therefore. Thick contrails cause both large LW and SW RF values. However, the correlation is far different from 100 % because the SW and LW effects depend on different input values (temperature, solar zenith angle, particle habits. particle sizes, system albedo, incoming solar irradiance and outgoing longwave irradiance) and respond to changes in the input parameters with different sensitivities. The correlations are zero during night, of course, and the day/night duration ratio and other input parameters are variable over the time period considered. Also, the day/night traffic ratio varied between the years. Therefore, several reasons caused different relative changes of net RF compared to the LW and SW components. We do not see a reason why the change in net RF should be always smaller than the change in the two components. This behavior may be peculiar to the situation considered.

My final major comment is that the paper seems like it would be best served by separation into two parts. The authors mention several times that they are in the process of developing a follow-on paper which will compare the model results to satellite data. It would appear much cleaner if the current manuscript were focused specifically on the model advances, rather than on the effect of COVID on contrail coverage. This would allow the aforementioned second paper to cleanly introduce both the model-based estimate of changes in contrail coverage due to COVID in a context where the results could be validated against observations. Naturally this is at the discretion of the authors, but such a division would resolve many of the concerns I have above.

We approach the problem stepwise. This paper describes the traffic and the contrail modelling. A companion paper (submitted) describes the results of a comparison with observations for 6 months. This is not the end of this line of research. Further studies are needed to explain the differences between the model and observation results because the observed changes are caused not only by contrails but also by other anthropogenic and natural effects. So this paper opens a new approach to study the climate impact of aviation and other anthropogenic changes during the COVID-19 pandemic..

Minor comments

Line 96: "Piston engine power aircraft only make a very small contribution" – a citation or quantification is needed for this.

We quantify the fraction of various aircraft types below.

Line 190: "The decrease of fuel consumption and flight distances are similar because the relative increase in aircraft weight (more cargo aircraft) is largely balanced by the lower load factor". Can you provide some quantification or reference? This is an interesting observation and potentially relevant to the discussion.

We quantify the aircraft mass below.

Line 420: The statement "The changes appear to be larger than expected" seems incorrect. Given the larger optical depth and narrower regional scope of this paper, the two studies seem to be in broad agreement – noting Sanz-Morère's discussion of the increase in overlap RF effects with optical depth.

We agree and will delete this statement in the revised version.

Traffic changes for different aircraft sizes and types

In response to the questions raised by Reviewer #1, we provide more detailed information on the changes in aircraft types and aircraft masses during the COVID-19 period. This information will be included in the revised version of the paper (either in the main text or in the supplement).

As a result of the sudden change in demand and permissions for air transport, fleet operations in 2020 were very different from 2019.

Table 1 compares total air distance covered in flights above FL180 over the European domain in March-August 2020 compared to March-August 2019. Here, aircraft are split into 5 mass classes, as explained in the table caption, depending on the maximum permitted take-off mass (MTOM), using BADA3 data for given ICAO aircraft types.

In April 2020, the total distance flown decreased to 8.8 % of the April 2019 values. The reduction was strongest for light and medium sized aircraft, i.e. single aisle transport and business jets, whilst general aviation aircraft (< 20 Mg) and heavy aircraft, i.e. twin aisle transport and cargo, experienced smaller reductions. By July 2020, light aircraft flight distances had returned to 70 % compared to the year before, whilst the average overall reduction was 23 % compared to July 2019.

Table 1. Flight distances (in Gm) of general aviation/military jets (G: MTOM < 20 Mg), light (L: 20 < MTOM <= 46 Mg), medium (M: 46 < MTOM/Mg <= 115), heavy (H: 126 < MTOM/Mg <= 395 Mg) and super heavy (S: 395 < MTOM/Mg) aircraft over Europe above FL 180, in the months April (4) and July (7), in 2019 and 2020; absolute values and percentage fractions of 2019 values.

Year	Month	G	L	M	H	S	Total
Absolute values							
2019	4	0.69	1.64	31.25	10.58	1.56	45.72
2020	4	0.16	0.12	0.82	2.37	0.51	3.98
2019	7	0.55	1.25	36.40	10.63	1.48	50.32
2020	7	0.39	0.35	7.42	3.04	0.49	11.68
Relative values							
2019	4	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
2020	4	22.8%	7.5%	2.6%	22.4%	32.6%	8.7%
2019	7	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
2020	7	70.6%	27.8%	20.4%	28.6%	32.8%	23.2%

Turbofan powered (jet) aircraft are responsible for most of the air distance flown at Flight Levels above 180 (>97.6 %) and for >99.6 % of all contrails, see Table 2. The contribution to air distance flown from turboprops is far smaller (<3.11 %) and even less for contrails (<0.36 %). The contrail contribution from piston-engine aircraft is below 0.05%, largely because they usually operate at altitudes below FL180.

Table 2. Total flight air distances and flight air distances with persistent contrails (in Gm) of jet, turboprop and piston-engine aircraft over Europe above FL 180, in the months April and July, in 2019 and 2020; absolute values and percentage fractions of monthly totals.

Year	Month	Jet	Turboprop	Piston	Total	Jet	Turboprop	Piston	Total
Flight distance									
2019	4	592.05	8.976	0.066	601.1	98.5%	1.49%	0.011%	100%
2020	4	51.31	1.648	0.040	53.0	96.8%	3.11%	0.076%	100%
2019	7	739.24	9.660	0.212	749.1	98.7%	1.29%	0.028%	100%
2020	7	247.92	5.957	0.105	254.0	97.6%	2.35%	0.041%	100%
Contrail length									
2019	4	45.59	0.119	0.001	45.71	99.7%	0.26%	0.003%	100%
2020	4	3.96	0.014	0.002	3.98	99.6%	0.36%	0.046%	100%
2019	7	50.29	0.018	0.008	50.31	99.9%	0.04%	0.016%	100%
2020	7	11.67	0.015	0.001	11.68	99.9%	0.12%	0.006%	100%