Dear Referee 2,

We thank a lot for your valuable comments and suggestions. We followed them as explained below.

The reviewers comments are repeated in **bold letters**, our replies are given in *italic*, and text modified or added to the manuscript is given in <u>blue</u>.

The authors use a regional scale model and contrail parameterization to simulate contrails and cirrus clouds occurring over central Europe during a single day – December 3rd, 2013. The simulated cloud cover and ice crystal mass mixing ratios are used in an online radiation scheme to understand the impact of aviation on direct and diffuse shortwave radiation reaching the surface, which in turn, affect the production of photovoltaic power. Overall, it is reported that aviation-induced cloudiness reduces PV power production by up to 10%. Assumptions related to the emissions index of ice crystals and crystal loss during the contrail vortex phase significantly alter this estimate. This is an interesting case study, which should be worth publishing in ACP; however, the limited time and spatial coverage of the reported model simulations limit the usefulness of authors' conclusions for broader understanding the relevance of aviation contrail cirrus to solar energy production. It certainly would be nice to see more data points for other spatial locations or time periods (e.g., summer). The following comments must be adequately addressed before I can recommend that this paper be acceptable for publication.

Thanks a lot for your review and your interest in our work. We see (and share) your opinion of the problem concerning the limited time and spatial coverage. However, this study should be seen only as a first step: developing the model, doing some comparison with observations and LES. Future studies with longer simulation time and other (larger) domains can follow this work.

A certain problem, at least with the presented setup is the following: The regional model needs lateral boundary data. From global models, we can get those information for the meteorology (partly also for gas phase and aerosols). However, neither data on contrails or contrail cirrus nor on aviationmodified cirrus clouds is available currently. Those would be needed to drive a model producing realistic results for longer time. Currently, several efforts to implement contrails into the ICON model are undertaken. Using this will overcome this issue.

Indeed, one day of simulation is not enough for providing a significant and statistically robust signal. We improved the figure that shows the time series of radiation related quantities by adding standard deviations as error bars.Furthermore, we additionally compare values for the mean for the entire simulation domain to the ones obtained for the selected area.

Further studies will follow, applying the model to other days, time of year, regions etc. to further investigate and enhance the significance (and relevance) of the influence of aviation on PV production.

1. Pg. 2, Line 16-17: This sentence is confusing. What is being claimed here – that this is the first time a regional scale model has been applied to study contrails and contrail cirrus? I don't think a statement like this is really necessary, but in any case, please be specific with what is being claimed as novel.

We delete the sentence in page 2, line 16-17:

"In this respect, the presented study is complementary to the aforementioned approaches and is, to our knowledge, the first study of its kind."

Instead, we add at the end of the corresponding paragraph:

Especially with respect to the spatial scale used in the regional scale COSMO-ART model, the presented study is complementary to the aforementioned approaches and is, to our knowledge, the first study of its kind.

2. Pg. 3, Line 12: What is the state of the art with respect to PV forecasts? There does appear to be some literature on this topic using both NWP and statistical models (e.g., Wan et al., 2015). Please expand this section to discuss current methods and considerations.

We change in page 3, line 9:

The presented model configuration serves to study microphysical evolution of contrails and contrail cirrus, their influence on natural high-level cloudiness, and their impact on the radiative fluxes on a regional scale and short time periods. This gains importance, e.g., in predicting the energy yield from photovoltaic (PV) systems, because additional cloud cover due to contrails is not represented in operational weather forecasting.

to:

The presented model configuration serves to study microphysical evolution of contrails and contrail cirrus, their influence on natural high-level cloudiness, and their impact on the radiative fluxes on a regional scale and short time periods. This gains importance, e.g., in predicting the energy yield from photovoltaic (PV) systems.

During the past decades, the development of alternative, clean energy production was enhanced to counteract global warming and reduce air pollution. Within the scope of methods, one of the most promising sources is solar energy, gained by PV cells.

To assure a sustainable supply, the demand of precise prediction of the energy yield from PV systems is desired (Lew and Richard, 2010). Several approaches exist to forecast PV power, such as statistical models, neural networks, remote sensing models and numerical weather prediction models (Inman et al., 2013). Especially PV forecast using numerical weather prediction models is challenged by special weather situations or phenomena that are poorly represented in the models (Köhler et al., 2017). E. g. Rieger et al. (2017) found a large impact of mineral dust due to Saharan dust outbreaks on the solar radiation over Germany. This becomes important, as mineral dust is currently not considered adequately in operational weather forecast.

Another phenomenon that is not represented at all in numerical weather prediction, is the influence of aviation.

References:

Lew, D. and Richard, P.: Western wind and solar integration study, Tech. rep., National Renewable Energy Laboratories, 2010.

Inman, R. H., Pedro, H. T., and Coimbra, C. F.: Solar forecasting methods for renewable energy integration, Prog. Energy Combust. Sci., 39, 535 – 576, 2013 doi: 10.1016/j.pecs.2013.06.002.

Köhler, C., Steiner, A., Saint-Drenan, Y.-M., Ernst, D., Bergmann-Dick, A., Zirkelbach, M., Ben Bouallègue, Z., Metzinger, I., and Ritter, B.: Critical weather situations for renewable energies – Part B: Low stratus risk for solar power, Renew. Energ., 101, 794–803, 2017 doi: 10.1016/j.renene.2016.09.002.

3. Pg. 3, Line 14-15 and Pg. 9, Lines 2-5: How are the flight radar data obtained and input into the model? How do these flight tracks compare/interface with the ADS-B data presented in Figure 2? Are these data publicly available, and if so, how can the reader obtain the data?

We change page 3, line 14-15:

"Another feature of this study is the new and recently developed data set of real time flight tracks. Rather than statistical calculations for globally averaged fuel consumption, the basic data consist of real time-based flight trajectories (flightradar24.com, 2015)" to:

Another feature of this study is the new and recently compiled data set of flight trajectories. Rather than statistical calculations for globally averaged fuel consumption, the basic data consist of real commercial aircraft waypoint data (flightradar24.com, 2015).

In Sec. 3.2 (Determination of Flight Tracks) we explain in more detail. We change page 9, lines 2 - 5:

"In addition to time, height and geographical position of the aircraft, information on aircraft type and current velocity is also available. In this study, besides position and time, we only use the wing span bspan as a proxy for the aircraft emission parameters (see section 3.1). " to:

Rather than statistical calculations for globally averaged fuel consumption, or radar data, the basic data consist of traffic waypoint information over a limited area recorded from ADS-B⁴ transponders on the plane (flightradar24.com, 2015). The ADS-B data is obtained mainly from flightradar24.com (2015). The DLR holds a historic data file that can be purchased from flightradar24.com (2015). This data is cleaned and combined with the input of the Official Airline Guide Database that is also hold by DLR.

From this information, a dataset is compiled, containing spatially and temporally resolved information on geographical position, height, current velocity and type of aircrafts. For reasons of efficiency, the information on geographical position is interpolated to fit onto the grid of the model. As a proxy for the aircraft emission parameters (see section 3.1), the wing span bspan is used. ⁴Automatic Dependent Surveillance - Broadcast

4. Pg. 3, Line 20: In the following what? This sentence is confusing.

We change in page 3, line 20: "In the following, ..." to: In this section, ...

5. Pg. 4, Line 21: How often and under what conditions are these limits actually reached in the simulations?

In general, critical processes are sedimentation and melting / sublimation of hydrometeors. To assure numerical stability, the limits are introduced within a clipping routine at the end of the microphysics. As mass and number concentrations are treated separately, it may occur, that at the end of a time step, e. g. due to sedimentation, a rather large value for the number concentration remains with a small amount of mass present or vice versa. This would result in unphysically small or large crystals. The same may occur during melting / sublimation. Here, in the first place, only the mass concentration is changed resulting in very small mean masses for the ice crystals.

Apart from this, the microphysical scheme is designed in a way to avoid reaching these limits. E. g. ice gets converted to snow via accretion or graupel starts melting when getting too large by simply sedimenting in lower and warmer layers.

About the "how often":

Tab.1 Occurrence of limits violated for both classes and simulations, each for simulation hour 12

	aviation		reference
	cirrus class	contrail class	cirrus class
m < m _{MIN}	0.002 %	0.005 %	0.001 %
m> m _{MAX}	0.03 %	-	0.03 %

In Tab.1, the relative occurrence of violated limits is shown for cloudy grid boxes both simulations and the classes considered for the 12th hour simulated. Note that only cloudy grid boxes (i. e. mass concentration > 0) are considered. Apparently, the limits for both classes are reached only rarely, also when including contrail ice.

For the case study shown, also the plots for effective radii (in Fig. 3, 4, 6, 7) may give a hint: Limiting the number concentration of ice crystals to assure a fixed mean mass (m) would result in a constant value for the effective radius ($r_e = r_e(m)$). As the respective plots show in large parts at least some variability over most areas for values of r_e , the limits most likely are not reached. 6. Pg. 5, Line 26-28: How are contrail and contrail cirrus ice distinguished from cirrus ice given the statement on Pg. 5, Line 5 that the cirrus and contrail cirrus ice classes are lumped together?

As mentioned in page 5, line 5, we cannot distinguish directly between contrail cirrus und natural cirrus directly, as soon as the contrail cirrus gets transferred to the "natural" cirrus class. The statement in page 5, line 26 – 28 actually refers only to the fact, that the contrail ice class is

represented in the radiation algorithm with its own cloud cover and optical properties.

The contribution to the natural cirrus class can only be seen comparing to the reference simulation. We change:

"To include contrails and contrail cirrus into the radiative algorithm, we include a contrail ice cloud cover determined from the contrail and contrail cirrus ice mass mixing ratio." to:

To include contrails and contrail cirrus in the radiative algorithm, we include a contrail ice cloud cover determined from the contrail ice class mass mixing ratio.

...

As mentioned before, the aviation contribution to the natural cirrus ice class can only be determined by comparison with the reference simulation.

7. Pg. 7, Line 26: Is there a citation for the assumed EI_iceno?

We add in page 7, line 26: ... following Unterstrasser, 2014.

8. Pg. 8, Line 18: What is the vertical resolution of the model?

We change in page 8, line 18:

"In the vertical direction, it is reasonable to assume that ice crystals are distributed over the whole grid layer."

to:

In the vertical direction, it is assumed that ice crystals are distributed over the whole grid layer. Close to the ground, the vertical grid size is about 10 m and increases to 300 m at the tropopause.

9. Pg. 10, Line 30: Is this sentence referring to Figure 3 instead of Figure 4?

This is true. We move it to the paragraph above.

10. Pg. 12, Line 3-4: What properties are being referred to here? I certainly wouldn't say that the number concentration in 4e and 4f are similar, and there are also large differences in IWC in 4b and 4c.

Changed:

"Again, the properties of the aged contrails and the natural cirrus around Germany are similar." to:

Here, local enhancements in both IWC and n occur in the cirrus ice class, where aged contrails are transferred to (Fig. 4e), compared to the reference simulation (Fig. 4f).

11. Pg. 14, Lines 11-12: Why do contrails only form at altitudes between 11 km and 13 km? Is this because air traffic is restricted to these altitudes on this line or are there lower altitude flights but the Schmidt-Appleman criterion is only satisfied at these altitudes?

Taking into account the rather high values for RHi also below 11 km, the Schmidt-Appleman criterion likely would be fulfilled.

But the traffic data we use hardly contains flights taking place below 11 km expect for climbing and descending. At least for the cross section selected, apparently none of these movements was taking place...

This is caused by the absence of air traffic below this layer.

12. Pg. 15, Line 6: Should the first word be "below"?

Changed "beyond" to below

13. Pg. 15, Line 10: Does the model account for downward subsidence of the aircraft vortices and plumes or is the vertical structure in the modeled contrails only due to gravitational settling of the larger ice crystals? The enhancements in ice number shown in Figure 6 appear to occur at flight level, but the enhancement in IWC is below flight level.

Change paragraph starting in page 15, line 5:

"In the aviation simulation, changes in the natural ice class can be found mainly at heights where contrails form and slightly beyond. Here, local increases in IWC and N occur. Keeping in mind the simple design of our model setup, those ice crystals represent both fall streaks of contrails as well as the transition into contrail cirrus."

to:

In the aviation simulation, changes in the natural ice class can be found mainly at heights where contrails form and slightly below of it. The enhancement of ice number concentrations occurs mostly at flight levels, whereas an increase in \$IWC\$ is found below. During the initialization, contrail ice crystals are vertically distributed over the whole grid layer and this indirectly accounts for the initial wake vortex induced vertical expansion of a contrail. Within our simulation, the vertical structure of the contrails is determined only due to the gravitational settling of the larger ice crystals.

14. I would like to see the satellite observations more directly integrated into the discussion surrounding Figures 3-4 rather than in its own section since I think that it can provide a lot of context and validation for the model results. Figures 8 and 9 as they stand now are kind of on their own and not particularly informative other than to denote that there are thin, high-level cirrus and no low clouds. The cirrus clouds shown in Figure 8a appear to be much more diffuse than the MODIS imagery for this time period, with the MODIS images showing a lot of contrail structure and providing a good snapshot of the time evolution of the scene during the two simulations. I suggest the authors strike Figures 8 and 9, and add MODIS satellite images at 1000Z and 1150Z either as part of Figures 3 and 4 or as a separate figure before them. Such an example figure created from worldview.earthdata.nasa.gov images is on the next page with detailed web references at the end of this review.

We have rewritten parts of section 4.3 (Comparison with Satellite Observation). We use the great source for images you suggest for both time steps considered. However, we refrain from including the discussion into the section before. There, we want to focus on the behavior of the model itself and consequences that arise thereof. A future study for situations where preferably in-situ measurements are available will then also include a more detailed verification and comparison with satellite data.



Figure 10. Top row: satellite image (MODIS True Color - Corrected Reflectance) (NASA/GSFC/ESDIS, 2018); center row: optical depth at 1.115 µm of all ice clouds for the aviation simulation; bottom row: optical depth of all ice clouds for the reference simulation; left column: 10 UTC; right column: 12 UTC.

In the following, satellite images (created with Global Imagery Browse Services (GIBS) NASA/GSFC/ESDIS, 2018) are shown in Fig. 10 for a qualitative assessment of the simulations. The panels a and b show the "MODIS Terra Corrected Reflectance True Color" at 10 UTC and 12 UTC for the simulated day, respectively, both with a resolution of 250 m. The "True Color" composition consists of MODIS bands 1, 4 and 3 (NASA/GSFC/ESDIS, 2018). Beside a cloud bank over the North and Baltic Seas and fog over Southern and Western Germany, a considerable number of line-shaped contrails and diffuse cirrus clouds are present across both satellite images. Main contrail clusters are found over Central Germany for both situations. Contrails can also be identified over the Netherlands and Belgium, over the Czech Republic, and south of the Alps. At 12 UTC, the rather widespread highlevel cloud cover seems to have decreased compared to 10 UTC.

Comparing Fig. 10a and Fig. 10e, obviously, the reference simulation underestimates the coverage of high clouds in the center of the domain, which, in large parts, consists of contrails and contrail cirrus Fig. 10c. Clearly, the amount of cloud cover seems to be underestimated also in the aviation simulation at 10 UTC. This discrepancy is probably due to the fact that air traffic was switched on at 08 UTC and earlier flight movements are disregarded in our simulation. Hence, the simulation evaluation at 10 UTC neglects all contrails older than 2 hours. The comparison at 12 UTC is more favorable and observations match much better with the aviation simulation than with the reference simulation.

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Acknowledgements:

We acknowledge the use of imagery from the Land Atmosphere Near real-time Capability for EOS (LANCE) system and services from the Global Imagery Browse Services (GIBS), both operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS, \url{http://earthdata.nasa.gov}) with funding provided by NASA/HQ.

15. What is the coordinate chosen for the red circle in Figure 11 and related time series analysis in Figure 12? Why was this coordinate chosen? Do the results change if a set of coordinates in the Δ SW < -5% band is chosen?

The red circle (53°N, 12°E) marks the center of an area of 140 km x 140 km. The curves in Fig. 12 thus represent an average over this area. But of course, the results slightly change, when looking at another location. Nevertheless, the overall patterns are similar there. We add to the description of Fig. 12.:

The red circle (53°N, 12°E) marks the location evaluated.

To draw more robust conclusions, we modify the evaluation of SW and PV reduction, by replacing Fig. 12 (now Fig. 13) with the following figure and text:

Fig. 13 shows the temporal evolution of incoming SW radiation and normalized PV power. Panels a to d represent mean values for the entire simulation domain, panel e additionally represents mean values for an area of approximately 50 km x 50 km centered at a spot in the north-eastern part of the simulated domain, indicated by the red circle (53°N, 12°E) in Fig. 12. This is the location of one of the largest solar parks in Germany (Solarpark Brandenburg-Briest). Also several other major solar parks are located around this area. For enhanced clearness, values for the sensitivity study (see Sec. 4.5) are depicted only as difference to the reference simulation. The differences between the aviation simulation and the reference simulation are in general more pronounced for the selected location that on average over the entire simulation domain.

During the whole time of daylight, contrails and contrail cirrus reduce up to 15 Wm² (about 7 %) of the total incoming SW radiation in the entire domain (Fig. 13a). The effect is largest during noon and ceases during the day. This corresponds to the size of contrail ice crystals. As in our simulation, contrails start to form at 08 UTC, the average contrail ice crystal size grows during the day. Accordingly, contrail ice effective radii also increase with time and lead to smaller values of the extinction coefficient.

Separating the total SW radiation into its direct (Fig. 13b) and diffuse (Fig. 13c) fraction, it is clear that especially the direct incoming SW radiation is strongly reduced by more than 20 Wm² due to the presence of additional ice crystals in the atmosphere.

In contrast, the diffuse incoming SW radiation is increased by up to 10 Wm². Enhanced scattering of SW radiation caused by the contrail ice crystals increases the diffuse SW radiation at the ground. Notably, the peak in reduction of diffuse SW radiation occurs in the afternoon, around 13 UTC. Between 08 UTC and about 11 UTC, the amount of diffuse SW radiation reaching the ground is larger in the aviation simulation. During this time, as mentioned before, contrail ice crystals are smallest on

average and forward scattering is less pronounced than for larger crystals, whereas contrail ice crystals grow on average during the day resulting in enhanced forward scattering.

In the aviation simulation, young and aged contrails generally reduce the incoming SW radiation at the surface. This effect is currently neglected in operational weather forecast models. However, this effect is of relevance for the production of solar energy. The temporal evolution of the normalized PV power is depicted in Fig. 13d) and Fig. 13e. The normalized PV is calculated using the open source PV modeling environment PV_LIB for python (Andrews et al., 2014). For a specific combination of a PV module and a PV inverter combination, a nominal power and a reasonable tilt is assumed. These technical specifications are taken from Rieger et al. (2017). They assume panels consisting of a south-oriented PV module with a nominal power of 220 W and a size of 1.7 m². Compared to the reference simulation, the normalized PV power is decreased in the aviation simulation most of the day. The largest losses of up to 10 % occur in the morning and diminish during the day, even an increase occurs for the selected location in the late afternoon (Fig. 13e). The normalized PV power is somewhat more strongly reduced than the total SW radiation. For production of PV power, the incoming direct radiation is of greater importance than the diffuse; of the two, the direct experiences the larger reduction from contrails and contrail cirrus.

The error bars in Fig. 13d and Fig. 13e represent the mean values +/- the standard deviation with respect to the entire simulation domain and the area of 50 km x 50 km around the selected location, respectively. The standard deviation in Fig. 13d reflects the large-scale variability of the impact of contrails and contrail cirrus on the incoming SW radiation, whereas Fig. 13e illustrates the small-scale variability.

Compared to the selected location, standard deviations are larger for the mean of the domain. Obviously, clouds modify the amount of SW radiation reaching the ground in a non-uniform manner. The magnitudes of the standard deviations for the aviation simulation are about the same magnitude like the ones for the reference simulation. Apparently, the impact of contrails and contrail cirrus on incoming SW radiation is as variable as the impact of natural clouds. E. g., even at 12 UTC, when the impact of contrails and contrail cirrus is largest, confined areas exist, which are unaffected by contrails and contrail cirrus (Fig. 11b).

However, the small-scale variability of the impact of contrails and contrail cirrus on SW radiation is rather small, reflected by much smaller standard deviations in Fig. 13e. One can therefore deduce that the exact location of contrails or contrail cirrus is not crucial for the strength of the impact on SW radiation.





16. Pg. 22, Line 20-21: Suggest rewording, "In reality..." to "This scenario explores lower engine soot emissions caused by either improved engine combustor technologies or fuel composition changes from, e.g., biofuel adoption (Moore et al., 2017). *We adopt your suggestion.*

17. Figure 2: Should this be COSMO-ART to be consistent with the text?

Actually, the name of the domain is not important. COSMO-DE is the domain, used by the German Weather Service to run their high resolved forecast for Germany We change the caption of Fig. 2 from "Flight trajectories for the COSMO-DE domain ..." Flight trajectories for the simulated domain ... 18. Figure 12: Please use a more descriptive legend and spell out abbreviations.

- We spell out the abbreviations.
- Reference
- Aviation Simulation
- lambda_Ns = 1
- El_iceno x 0.1



References Cited: Wan et al. (2015) "Photovoltaic and Solar Power Forecasting for Smart Grid Energy Management", CSEE Journal of Power and Energy Systems, 1(4). doi:10.17775/CSEEJPES.2015.00046, http://ieeexplore.ieee.org/document/7377167/.

NASA Worldview Viewer with imagery and orbit tracks:

https://worldview.earthdata.nasa.gov/?p=geographic&l=VIIRS_SNPP_CorrectedReflectance_TrueCol or(hidden),MODIS_Aqua_CorrectedReflectance_TrueColor,MODIS_Terra_CorrectedReflectance_True Color,Aqua_Orbit_Asc,Terra_Orbit_Dsc,Reference_Labels(hidden),Reference_Features(hidden),Coast lines&t=2013-12-03&z=3&v=-17.06324930328618,31.036661088764802,35.3750429177626,68.8713 518 6462584

Time stamp information for the Terra and Aqua images is shown on the orbit tracks. Editable Link to 1000Z Terra Image JPEG:

https://gibs.earthdata.nasa.gov/image-

download?TIME=**2013337**&extent=**3,45,20,56**&epsg=4326&layers=**MODIS_Terra_CorrectedReflecta nce_TrueColor**,Coastlines,Reference_Features&opacities=1,1,1&worldfile=false&format=image/jpeg &width=**1080**&height=**768**

Similarly, for the 1150Z Aqua image JPEG:

https://gibs.earthdata.nasa.gov/image-

download?TIME=**2013337**&extent=**3,45,20,56**&epsg=4326&layers=**MODIS_Aqua_CorrectedReflecta nce_TrueColor**,Coastlines,Reference_Features&opacities=1,1,1&worldfile=false&format=image/jpeg &width=**1080**&height=**768**

where coloring denotes: Year and Julian Day, Bounding Coordinates, Layer, Image Dimensions in Pixels (controls resolution, aspect ratio)