Responses to anonymous reviewer #2

We thank all reviewers for their helpful advices and constructive comments about our paper. Their suggestions and criticism have led to a strongly revised and restructured version of our manuscript where we concentrated on two goals: (1) we develop a new method to identify microphysical properties of contrails, contrail cirrus and natural cirrus in the same meteorological conditions from in situ measurements, (2) radiative forcing of contrail cirrus and natural cirrus are derived by satellite observations based radiative transfer modeling in air traffic region favorable for contrails evolution. To this end, we have modified pictures and removed some of them, made the text more concise, added a supplement and wrote clearer explanations.

We thank the referee for highlighting the importance of the study and for helpful comments, which we address in the revision of the manuscript.

In the following we number the referee`s comments (RC) and reply (R) to them individually.

RC: Summary of paper:

The authors use a combination of aircraft and satellite measurements, and radiative transfer modeling to analyze a band of thin ice cloud in the North Atlantic air corridor on 26 Mar 2014. (Young) contrails, contrail cirrus, and natural cirrus within the cloud layer are distinguished by in situ measurements of ice particle number concentration and NO gas concentration. The optical thickness, effective radius, and radiative forcing are computed for each cloud type within the cloud band.

General comments:

RC1: The goals of the paper are scientifically important and worthy of study, but the authors do not characterize the three cloud types in a convincing manner. The cloud types are defined from in situ measurements, but the authors appear to conflate individual contrail properties to the entire layer at the point of observation. It is not clear what distinguishes a (young) contrail from contrail cirrus, even without the context of the overall cloud band. Several if not most of the contrails appear to be at least two hours old and would likely be visible in the satellite imagery, yet I could find no attempt by the authors to use MSG/SEVIRI satellite observations to classify (or determine the history of) any possible contrail cirrus cloud. In fact, the authors seem to claim that such a distinction is not possible, with an example of an ambiguous contrail encounter between 0843 and 0845 UT to demonstrate the current difficulties in discriminating between young contrails and contrail cirrus. Thus, it seems as though the separation of the cloud observations into different types is essentially meaningless. Add on top of that the difficulties in assigning the properties of individual contrails to the entire cloud layer, the overall usefulness of classifying different points of the cloud as contrail, contrail cirrus, and cirrus is minimal. Although it is clear that new and better definitions of aviation-induced and -influenced ice clouds are necessary, I'm not sure how the authors can proceed to strengthen the paper. Perhaps a more careful study of the numbers and ages of the contrails within a layer may allow for a more useful definition of how much a cirrus layer is influenced by aviation.

R1a) author's response

We thank the reviewer for his/her critical discussion of our manuscript which helped to shorten, strengthen and to reshape the manuscript. We now use the aircraft data together with high resolution satellite data to assess the situation and find an ideal contrail cirrus outbreak event, thin natural cirrus with many contrails and contrail cirrus and hence a large aviation impact. As suggested the study of the numbers and NOx/ages of the contrails and contrail cirrus from airborne in situ or lidar analysis gives information on the magnitude of the aviation influence on the cirrus and helps to achieve consistency between the different data sets with different resolutions.

We note that MSG/SEVIRI satellite observations with the 15min/5min repeat cycle are functions of both time and space and this causes the temporal and spatial difference between in situ and satellite observations. Based on the referee's comments, to ensure a more in-depth understanding, we discuss the evolution of the contrail cirrus outbreak for the entire layer from satellite RGB images, brightness temperature differences (BTDs) and simultaneous air traffic dataset. We add highly resolved MSG/SEVIRI data which clearly show linear contrails and we consider the evolution of this contrail cirrus outbreak situation in a given area, see new Fig. 2 in the manuscript or Fig. A1 below. In part, contrails are visible in the BTDs, but not all of them, since their effective radii are not as small as those of fresh contrails and they thus lead to smaller BTDs. In addition, some of the contrails partly overlap in the low resolution BTDs and appear "smeared out". This hinders an automatic detection using e.g. the algorithm by Mannstein et al. (1999, 2010). While we removed the identification of contrails from the satellite images, as suggested by the referee, we overlap in situ information on cirrus on the top of satellite pictures and confirm satellite observed contrail cirrus and natural cirrus with cirrus information from in situ and lidar measurements even considering temporal and spatial difference. We also have added the flight direction. To constrain the manuscript, the analysis about satellite retrieval R_{eff} and IOT based on the in situ cirrus classification was removed.

Moreover, we now focus on the cycle of TOA RF of the contrail cirrus outbreak event in the area of the HALO flight over 8 h from early morning to afternoon and then operate satellite observations based radiative transfer modeling to assess their radiative impact. We find warming contrail cirrus in the early morning and cooling contrail cirrus during the day. We hope that the revised version of the manuscript now more clearly supports the conclusions.

References

Mannstein, H., Meyer, R., and Wendling, P.: Operational Detection of Contrails from NOAA-AVHRR-Data, Int. J. Remote Sens., 20, 1641–1660, 1999.

Mannstein, H., Brömser, A., and Bugliaro, L.: Ground-based observations for the validation of contrails and cirrus detection in satellite imagery, Atmos. Meas. Tech., 3, 655–669, https://doi.org/10.5194/amt-3-655-2010, 2010.

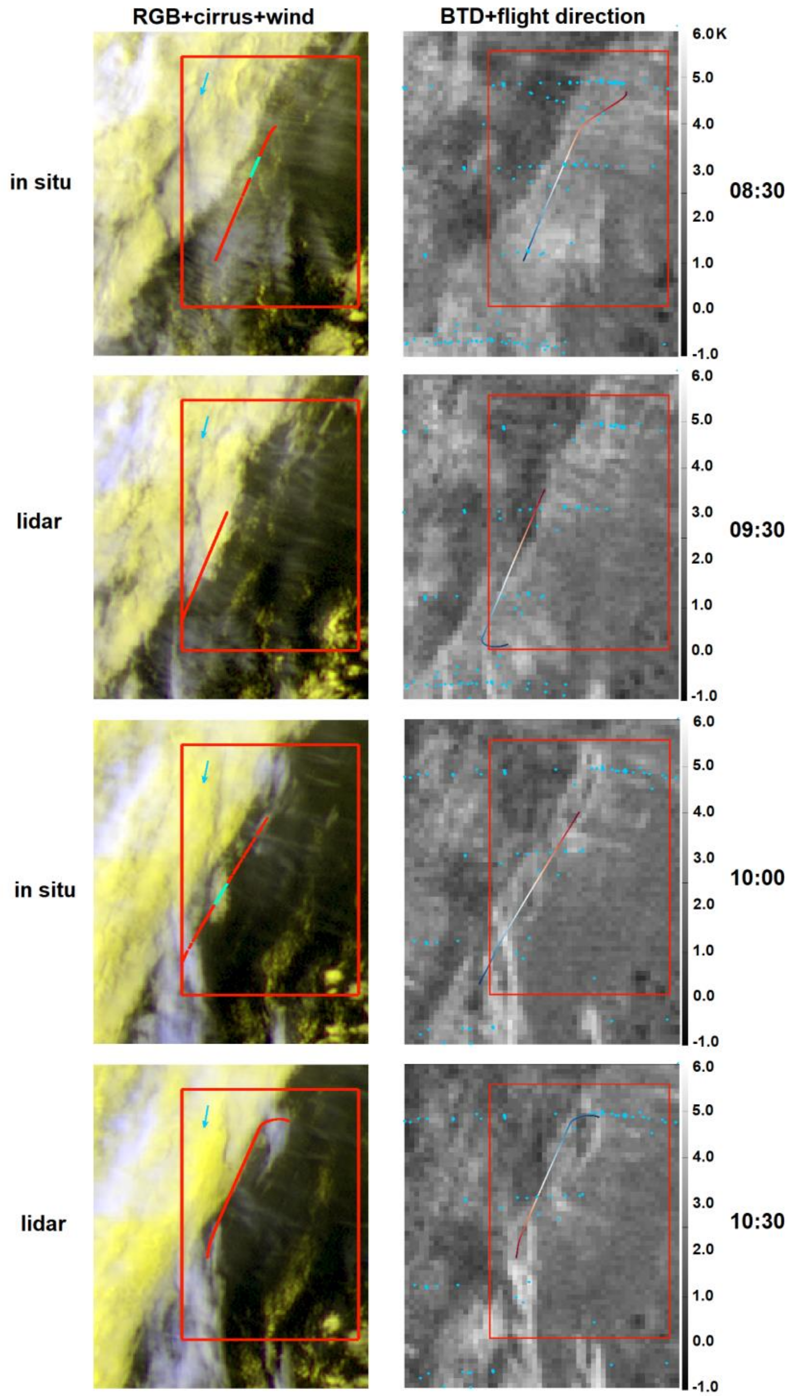

Figure A1: Time series of contrail cirrus and surrounding clouds from MSG/SEVIRI observations over the NAR corridor on 26 March 2014. The first column: RGB-composite with overlaid cirrus, low-level liquid clouds pixels and in situ/lidar leg at close time. The red and green line of the HALO flight track represent contrail cirrus and natural cirrus, respectively. The blue arrow indicates the wind direction, which is almost perpendicular to the line shaped contrail cirrus. The second column: 10.8 µm and 12.0 µm BTD (K) with overlaid cirrus pixels. Blue points show air traffic dataset interpolated to MSG grid from M3 and NATS. The color of the HALO flight track indicates the flight direction. HALO flies from red to blue part. Top to bottom: 08:30, 09:30, 10:00 and 10:30 UTC. The red area is investigated in Sect. 4.2.

Specific comments:

RC2: The exposition of the research in the paper is not always easy to follow. For example, it is hard to see the details of the flight path in Figure 2, especially in the blue lines in the lefthand RGB-composite images. The lack of clarity makes it difficult to compare the flight path to the lidar data from Figures 3 and 4. Crucially, the authors never directly inform the reader about the flight path details (including three lidar legs and three in-situ legs) until Figure 6, leading to much confusion for the reader in Section 3.2. Several of the following comments highlight similar difficult-to-follow text.

R2a) author's response

Thanks for commenting on this ambiguity. We change Fig. 2 (see comment above) and add highly resolved MSG/Seviri data showing line shaped contrail cirrus during the HALO flight. We replace the entire HALO flight track with the HALO leg close to the time of satellite observation. To make it clear and easy to compare the flight path to the lidar data from Fig. 3 we put Fig. 4 on RHi in the supplementary material S2, and we mark the flight direction of HALO in each plot. We also add information on the wind direction, which is almost perpendicular to the line shaped structures of the contrail cirrus. We modify Fig. 2 and the related text accordingly.

R2b) manuscript changes

L229-230: "Figure 2 presents the temporal variation of contrails and surrounding clouds with one HALO in situ/lidar leg at close time and air traffic data 2 to 3 hours before from 08:30 (the first in situ leg) to 10:30 UTC (the third lidar leg)."

L247-253 (caption): "Time series of contrail cirrus and surrounding clouds from MSG/SEVIRI observations over the NAR corridor on 26 March 2014. The first column: RGB-composite with overlaid cirrus, low-level liquid clouds pixels and in situ/lidar HALO leg at close time. The red and green line of the HALO flight track represent contrail cirrus and natural cirrus, respectively. The blue arrow indicates the wind direction almost perpendicular to the line shaped structures of the contrail cirrus. The second column: 10.8 µm and 12.0 µm BTD (K) with overlaid cirrus pixels. Blue points show air traffic dataset interpolated to MSG grid from M3 and NATS. The color of the HALO flight track indicates the flight direction. HALO flies from red to blue part."

RC3: Line 235 (Figure 2): It is suggested here, but not entirely clear, but have the blue flight segments in Figure 2 been adjusted to account of the 12-minute difference between the nominal satellite time and the actual time of the image acquisition?

R3a): author's response

Thanks for commenting on this ambiguous part. Yes, we have computed the line acquisition time according to the SEVIRI metadata. The cross already indicates the time of simultaneous SEVIRI and HALO measurements. Our new plots contain the direction of flight of HALO (from red to blue). But we removed the comparison of in-situ and remote sensing data, and overlapped satellite images with in situ/lidar leg at close time. Changes in the text are given in the answer section to specific comment #1 concerning the flight track and direction in Fig. 2.

RC4: Section 3.1: The peaks in backscatter during Leg 2 look like individual contrails. It is not clear how the lidar observations compare with the HALO aircraft flight path. Figure 2 suggests that most of the flight legs are perpendicular to the NAR corridor traffic but some legs around 0800 are parallel to NAR corridor traffic. What direction is HALO flying relative to NAR corridor during Legs 1, 2 and 3 in Figure 3?

R4a): author's response

Sorry for the unclear description. The HALO flight direction could be determined from the indication of latitude in Fig. 4f, but to show it clearly Figure 2 is now updated with lidar leg 2 at 9:30 and lidar leg 3 at 10:30 and with flight their direction. The HALO flight was perpendicular to the Northern Atlantic Flight (NAF) tracks and perpendicular to the contrail cirrus seen on the satellite images in Fig. 2. In addition, we now give the wind direction almost perpendicular to the line shaped structures of the contrail cirrus. We changed the text accordingly.

R4b) manuscript changes

L224-229: "On 26 March 2014 the HALO aircraft started from Oberpfaffenhofen in Germany at approximately 05:30 UTC and probed the cirrus over NAR from around 08:00 to 11:30 UTC with a race track pattern between approx. 51.5°N and 54°N at a longitude of ca. -14°E (-13.6 to -14.4°E), see the flight track in Fig. 1a and also Voigt at al. (2017, Fig.4). In this area, HALO flew 3 lidar legs almost perpendicular to the NAR tracks (07:57 UTC - 08:35 UTC, south to north, 09:17 UTC - 09:30 UTC, north to south, and 10:21 UTC - 10:52 UTC, south to north), each followed by in situ legs at different altitudes."

RC5: Line 311: "properties collected during the three legs." Which three legs? The legs described in Figures 3 and 4? Don't the authors state that those are WALES measurement legs and thus "can neither be directly inter-compared nor directly compared to in situ observations taken in between"? How is the reader to know that Figure 5 possible, unless the authors tell the reader beforehand that there are 3 lidar legs and 3 in-situ legs?

R5a) author's response

We think that the long sentence here gets the reader confused. Original L310-311 shows that the general overview of R_{eff} against N is obtained from in situ legs. But ultimately the whole sentence was removed to shorten this version of manuscript. In L224 to 229 we have added the general explanation of flight pattern analyzed in our study. In addition, Figure 4 gives detailed information on the flight path, direction and altitude of the lidar and in-situ flight legs.

RC6: Figure 6: The reader cannot discern any (young) contrails (blue color) in Figure 6d. I suggest this be removed from the figure. Lines 404 through 406 state that only 1 percent of the observations are (young) contrails.

R6a) author's response

We now update Fig. 4d with a new version that gives the cirrus classification from in-situ data more clearly and explicitly. A large fraction of the measured cirrus has been identified as contrail cirrus, in addition some natural cirrus has been measured. Some shot sequences of contrail encounters are also visible, we think this information is helpful to the reader and explains the contrail cirrus outbreak event as observed with in situ data.

RC7: Line 400: The discussion about number concentration (N) at this point appears muddled. "Ncas occurrences decrease by more than 2-3 orders of magnitude from 0.03 to 0.78-0.84 cm^{-3}." Shouldn't this read occurrences increase by more than 2-3 orders of magnitude"?

R7a) author's response

Thanks for commenting on this description. We plot a histogram of used in-situ measured N from CAS and CIP and ΔNO on 26 March 2014 over NAR. It has a general range of 0 to 1 cm^{-3}. We take a value in the middle (0.4 cm^{-3}) as separation between high N_{CAS} peaks attributable to contrails and moderate values of N_{CAS}<0.4 cm^{-3} that we assign to older contrails/contrail cirrus. The values from 0.03 to 0.78-0.84 cm^{-3} is not the increase of magnitude but the range within which the Ncas occurrences decrease by more than 2-3 orders. The related description is moved to the supplement S2 and changed accordingly. We added Fig. S2 in the supplement to present the histograms of in-situ measured Nice from CAS and CIP and ΔNO on 26 March 2014 over NAR.

R7b) manuscript changes

Ultimately the sentence was removed in the revised version of manuscript in order not to confuse the reader.

RC8: Section 3.2.1: The discussion in this section implies that most of the contrail cirrus observations are from contrails at least 2 h old. How old are the (young) contrails estimated to be?

R8a) author's response

We thank the referee for your suggestions. The contrails are estimated to > 18 min according to Schumann et al. 1998. Young contrails can only be classified using in situ measurements. In order to avoid confusion, we constrain our new manuscript version to two categories in satellite data, aviation-induced and influenced ice clouds or not from satellite remote sensing. Updates in the Fig. 2 and the text are given in the answer section to general comment #1.

RC9: Lines 407-409: "We finally remark that MSG/SEVIRI satellite observations are left unused for this classification since the distinction between contrail cirrus and natural cirrus from satellite observations is inherently difficult due to the typical characteristics of young contrails - large N - cannot be measured by passive sensors." This statement conflates (young) contrails with contrail cirrus, and would thus make all of the previous discussion from Table 1 classifying each cloud type meaningless.

R9a) author's response

Thanks for your critical comments. Table 1 classify contrails, contrail cirrus and natural cirrus from in situ probed properties. For the aspect of passive satellite observations, the only objective signature of air traffic is the linear shape of the contrails and their higher BTDs since they contain small ice particles. For contrail cirrus there is no objective criterion. We admit the difficulty to distinguish contrails and contrail cirrus, and we now combine contrails and contrail cirrus as the former accounts for a small proportion of the data. Updates in the Fig. 2 are given in the answer section to general comment #1. Ultimately this sentence was removed in the revised version of manuscript.

RC10: Section 3.2.2: This section is poorly worded and misleading. We are not simply looking at the temporal evolution of cloud properties, but variables changing in time and space. The following sentences explain that and thus contradict the beginning sentence. The description of how the SEVIRI measurements are classified according to the HALO observations is a bit unclear. Given that the SEVIRI and HALO measurements might be displaced by as much as 7.5 min, and the total time of the (young) contrail observations is around 110 s (1 percent of 3 h), it it not surprising that the R_{eff} measurements between HALO and CiPS are not correlated, and that no significant difference between the IOT between contrail snd contrail cirrus was found. Even without the fall streaks, it seems unlikely that the properties of individual (young) contrails can be determined from the SEVIRI data generally.

R10a) author's response

We thank the referee for this important comment. We agree and changed the manuscript accordingly. In general, we think that it is possible to investigate the properties of contrails using satellite data, as in Vázquez-Navarro et al. 2015, where contrails were tracked with time. However, the difference in acquisition time between satellite and HALO can lead indeed to mismatches that make it difficult to investigate contrail properties starting from in situ observations. For contrail cirrus the situation is different since these measurements, as shown now in our new plots, are more numerous and form connected regions. Nevertheless, in order to strengthen our paper and reach clear goals we restructured the paper. We have removed Sect 3.2.2 including the analyses about IOT and CTH from satellites, the cirrus classification for MSG/SEVIRI observations according to HALO measurements, and the inter comparison of R_{eff} from in-situ and remote sensing data. Now we use in situ data to characterize microphysical properties of contrails / contrail cirrus / natural cirrus and satellite data to determine the RF of the contrail outbreak.

RC11: Lines 453: Most estimates of contrail optical thickness from polar orbiting IR sensors are from clouds at least 2 h old, and thus may not the the young contrails that are implied here. The estimated age of the contrails is not mentioned until line 476 after much discussion about IOT estimates of "contrails". The terms contrail and contrail cirrus are being mixed together and it is unclear what the authors are talking about in this section.

R11a) author's response

Thanks for the comments on this section. We took some literature to discuss the variation of IOT as a function of contrail ages. We agree that the term of (young) contrails should not be used here. Ultimately the whole paragraph was removed to shorten this version of manuscript and strengthen the main goals.

RC12: Lines 478-479: "From the point of view of optical thickness, the entire cloud seems to be homogeneous without remarkable differences among the cloud types defined in Sect. 3." This statement reinforces the overall lack of utility of the cloud types.

R12a) author's response

We still think that the ridge cirrus, at the SEVIRI resolution, has a comparable IOT in the segments that are characterized as contrail cirrus or natural cirrus. Nevertheless, similar with the answer to specific comment #10, we have sharpened our goals, emphasized the difference between in situ and satellite imagery in time and space, and removed Sect 3.2.2 including the analyses about IOT and CTH from satellites, the cirrus classification for MSG/SEVIRI observations according to HALO measurements, and the inter comparison of R_{eff} from in-situ and remote sensing data.

RC13: Figure 8: The caption in this figure is not helpful. The cloud properties measured by CiPS are necessarily "at SEVIRI spatial resolution" while the R_{eff} measured by HALO are concurrent and collocated aircraft measurements.

R13a) author's response

Sorry, Fig. 8 was removed in the revised version to shorten and strengthen the manuscript.

RC14: Line 437 (Figure 8): What times is HALO in the northern part of the race track? Why make the reader determine these times on their own from Figure 6, but not the southern part of the race track?

R14a) author's response

We thank the referee for his/her suggestion and make the time of HALO in the northern part of the race track clear in original L437-438 as "In the northern part (i.e. at ~09:15, 10:00, 11:30UTC) of the HALO race track, IOT is between 0.05 and ~0.3, sometimes reaching up to almost 0.4." Ultimately Fig. 8 and the corresponding explanations were removed in this revised version of manuscript.

RC15: Lines 528-529: "Finally, we jointly assess radii variations of natural cirrus and adjacent contrail cirrus from CiPS with simultaneous HALO measurements for this NAR case." Please tell the reader that this section refers to Figure 8.

R15a) author's response

Thank you for your comment. This section refers to Fig. 9 according to the combination of Fig.8 and the cirrus classification results from original Fig. 6d. We correct text would read "Finally, we jointly assess radii variations of natural cirrus and adjacent contrail cirrus from CiPS with simultaneous HALO measurements for this NAR case based on Fig.8 and the cirrus classification results from Fig. 6d."

We removed the discussion of the comparison of R_{eff} from in situ measurement and satellite remote sensing from the manuscript, as further analysis showed considerable uncertainties.

RC16: Lines 535: "The temporal variability of CiPS R_{eff} along the flight path…" The authors again appear to neglect that even satellite measurements are functions of both time and space. Simply say "The variability of CiPS R_{eff} …". Also, say "than that of collocated in situ R_{eff}" instead of "than that of simultaneous in situ R_{eff}". If the data are averaged over the MSG/SEVERI pixels, they can't be simultaneous. One quantity is time averaged while the other is not.

R16a) author's response

Thanks for pointing out this ambiguous part once more. We emphasized that satellite measurements are functions of both time and space and updated "the temporal variability of CiPS R_{eff} along the flight path". Ultimately Fig.8 and the corresponding explanations were removed in this revised version of manuscript.

RC17: Section 4.4 and Figure 13: Why include this section? Isn't this redundant because the authors have already compared collocated satellite and HALO observations? Why are the various regional quantities computed until 18 UT when only HALO and SEVIRI observations from 0830 to 1230 UT were presented earlier in the paper? Why does a positive vertical velocity imply "the local downward motion of airmass to warmer temperature layers". Doesn't positive vertical velocity mean upward motion of airmasses?

R17a) author's response

Thank you for your points. The reason why this section is included is because "In order to examine microphysical properties and radiative effects of the contrail cirrus outbreak detected in this area and to analyse the corresponding temporal variation", as L429-430 indicates. In the original version of manuscript under discussion, it is also to examine whether cirrus detected during the HALO flight are representative of this area and this time. Thus, this isn't redundant although we have already compared collocated satellite and HALO observations.

We originally computed various regional quantities until 18 UTC to show the diurnal cycle of TOA RF of ice clouds in the area. As HALO left the area around noon, we only present HALO and collocated SEVIRI observations from 0830 to 1130 UTC.

We performed more analyses at early morning around 6 to 7UTC and limited the cycle of TOA RF of the contrail cirrus outbreak in the range of 6 to 14 UTC before and after the HALO flight. The corresponding Fig. A2 in this answer adapted Fig. 7 in the revised version of this manuscript. The new time span helps to between distinguish the positive warming contrail cirrus during the night and early morning and the cooling contrail cirrus outbreak during the day.

The positive or negative vertical velocity are defined in the website of “ERA5 hourly data on pressure levels from 1959 to present” in Climate Data Store. Specifically, “Vertical velocity can be useful to understand the large-scale dynamics of the atmosphere, including areas of upward motion/ascent (negative values) and downward motion/subsidence (positive values)”. Thus, the positive vertical velocity means downward motion of airmasses. We removed the vertical velocities from the figure and highlight the most important information, a positive and negative radiative forcing of this contrail cirrus outbreak.

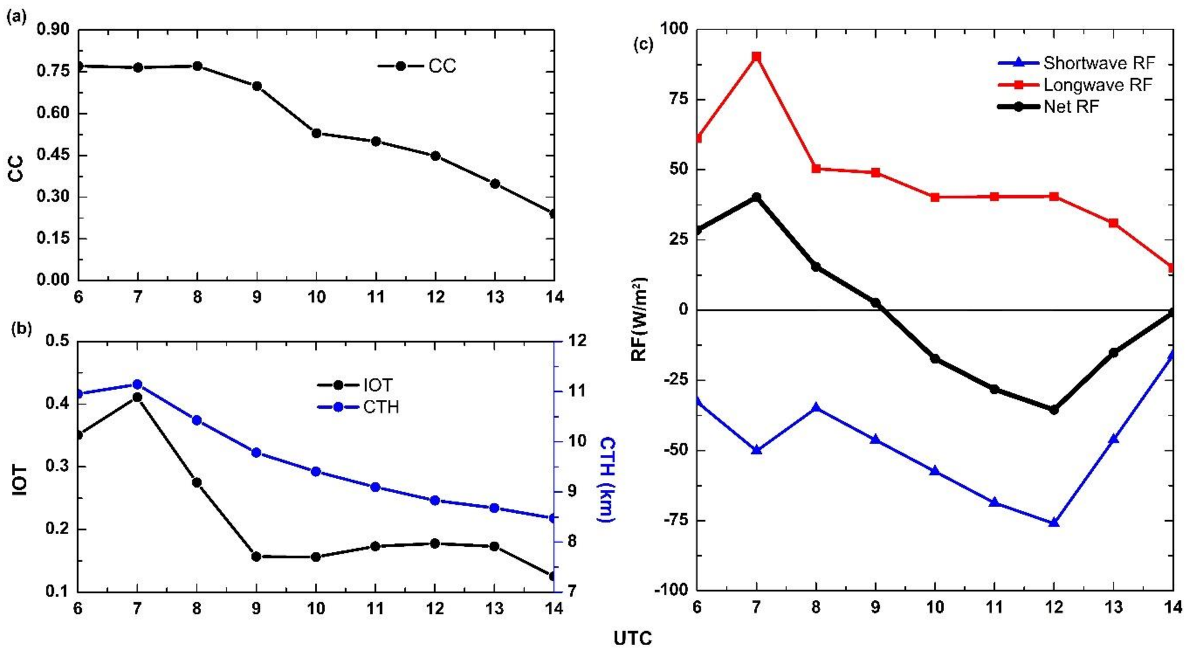

Figure A2: The variations of (a) CC, (b) mean IOT and mean CTH, and (c) SW, LW and net RF within the area indicated by a red box in Fig. 2

R17b) manuscript changes

L454-463: “In Fig. 7a, we observe that CC gradually decreases from 0.77 at 06 UTC to 0.25 at 14 UTC. The positive vertical velocity from ERA5 around that region implies the local downward motion of airmass to warmer temperature layers and the CTH also decreases. IOT in Fig. 7b decreases between 07:00 (0.41) and 10:00 UTC (0.15), then slowly increases until 12 UTC (0.17), then falls to 0.12. CTH decreases during the day and is thus consistent with both the observations of HALO (Fig. 3) and the downward motion. Since an underestimation of CTH by CiPS with respect to WALES (Fig. 3) is observed there, we assume that CTH is also underestimated by CiPS in this area.

Mean net RF over this area in this synoptic situation is positive in the early morning until 9 UTC with the maximum of net RF is at 7 UTC when the sun has risen. Hence the contrail cirrus outbreak is warming during night and early morning hours. After 9 UTC, the forcing becomes negative. More explicitly, from around 9 to 14 UTC the net RF is negative and thus this contrail cirrus outbreak tends to cool during daytime. The strongest cooling is observed at 12 UTC."

Typographic errors and other minor issues:

RC18: Lines 162-163: "For CTHs larger than approx. 8 km, CTH has an absolute percentage error of 10%, with underestimation for CTH > 10 km at 50° N and overestimation for CTH < 10 km at the same latitude." What does this mean? That CTH is underestimated when the measured CTH > 10 km but overestimated with the measured CTH < 10 km?

R18a) author's response

Yes, the meaning of this sentence is that is.

RC19: Line 188: I don't think that "detailly" is a valid word. Perhaps "in detail" would be better here, or simply say that both water and ice clouds are represented in the model (It is assumed that they would be represented realistically as possible by the model.)

R19a) author's response

Replaced with "in detail" in L184.

RC20: Line 199: Change "transit to" to "transition into".

R20a) author's response

Replaced with "transit into" in L200 as it should be a verb.

RC21: Figure 2: Time series of contrail cirrus… sounds better than "Temporal variation of contrail cirrus" in the figure title.

R21a) author's response

Replaced with "Time series of contrail cirrus" in caption of Fig. 2 in L247.