RC2

Interactive comment on “Statistical Analysis of Contrail to Cirrus Evolution during the Contrail and Cirrus Experiments (CONCERT)” by Aurélien Chauvigné et al.
Anonymous Referee #2
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The authors present aircraft observations of the scattering properties of ice crystals and the trace gas properties sampled inside 17 contrails during two phases of the CONCERT field experiment. While the results presented here are relevant and interesting, the paper has several areas where more explanation is warranted before I can recommend it for publication. For example, some parts of the introduction need to be reorganized.

RC : The most major flaw of the paper which needs to be address is the selection of the clusters. The authors base their cluster classification on a rough examination of the first three principal components in the x-y plane and seem to draw ellipses around where they “roughly identify” where the clusters are. However, with recent advances in machine learning, there are more objective methodologies for classifying data into clusters, with the most applicable methodology for a feature space of three variables to be k-means clustering. The authors should either better justify why their current ellipses were chosen and why the feature space was used for the PCA, or use automated clustering techniques.

Finally, I think a section on how their contrail cirrus observations fit in with past studies is warranted, since the paper lacks much discussion on how their observations fit in with what is already in the literature. I list some other comments below.

We would like to thank the reviewer for his interesting and constructive suggestions. We have tried to follow every suggestion in order to improve the manuscript. Each reviewer's comments are addressed and the manuscript has been modified accordingly.

A significant change in the paper concerns the implementation of an automatic clustering method (k-mean method) to enhance the statistical significance of the contrail phase discrimination. Subsection “*3,2,2 Clustering analyses*” has been added and gives details of the method. After some tests we found that 16 clusters are necessary to classify the patterns revealed by the PCA analysis. To be in accordance with ATC observations, clusters 8 to 16 deduced from the k-mean method (Figure RC2.2.a.) were gathered into two clusters (A and B, Figure RC2.2.b.). Clusters 2 to 5 have also been merged to one single cluster.

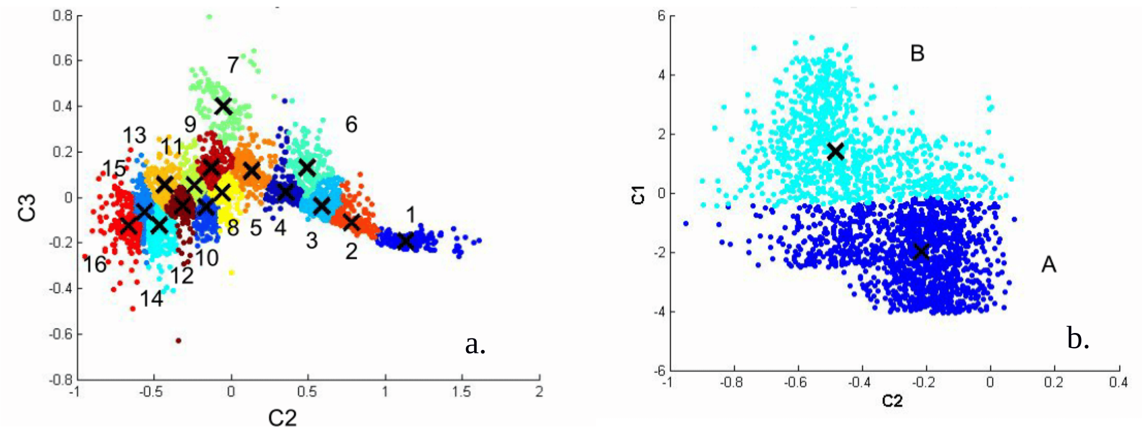

Figure RC2.1.: Clustering analyses according k-mean method. a) First step using 16 clusters and b) second step grouping clusters 8 to 16 to two clusters (A and B).

The following table summarizes the correspondence of the clusters defined by the k-mean methods and the cluster's definitions according to ATC information:

k-mean clusters	Cluster number	definition	name
1	0	Primary Wake	**PW**
6	1	Young Contrail 1	**YC1**
2, 3, 4 and 5	2	Young Contrail 2	**YC2**
A	3	Aged Contrail 1	**AC1**
7	4	Aged Contrail 2	**AC2**
B	5	Cirrus Cloud	**CC**

Table RC2.1: Cluster definition according the k-mean method.

Comments:

Major comments:
Lines 51-91. This paragraph is too long and needs to be reorganized. For example, there is too much detail on how NO from aircraft exhaust is converted into acids that does not really add to the major point that NO interacts with OH to make nitr(ic)ous + sulfuric acid. I also feel that this can really be 3 paragraphs: one about NO interacting with OH to produce acids, one about the contrail production process and one about the contrail aging process.

The structure of the introduction has been changed and two subsections were added, namely:

1.1. Contrail formation and evolution
1.2. Optical and microphysical properties of contrail phases

Moreover, the description of contrail chemical properties has been shortened.

Modifications:
l.55: "*Several studies in the past have been dedicated to the evolution of concentrations of nitrogen oxide (NO) and sulphur dioxide (SO_2) and their oxidized forms (Kärcher and Voigt, 2006 ; Voigt et al., 2006 ; Schäuble et al., 2009 ; Jurkat et al., 2011).*"

Line 109-146: I feel that a lot of the individual data points cited here are better suited for an extra section in the paper comparing your contrail observations against past studies. Right now, no link is made to how your categories compare against these past observations and I think such a comparison is needed in order to justify that the range of values that you observe in your clusters correspond to contrails properties that are observed in nature. Therefore, I recommend shortening this paragraph to
just briefly explain how the microphysical properties of contrails evolve with time with leaving specific numbers to a later comparison.

The paragraph has been shortened and we compared our contrail observations against past studies in section 4.2. In particular, average microphysical properties of the clusters were compared with the main findings of Voigt et al. (2017), Schumann et al. (2017) and Atlas et al. (2005). We also discussed the shortcomings related to the interpolation of the PSD and its impact on the derived microphysical quantities.

Modifications:

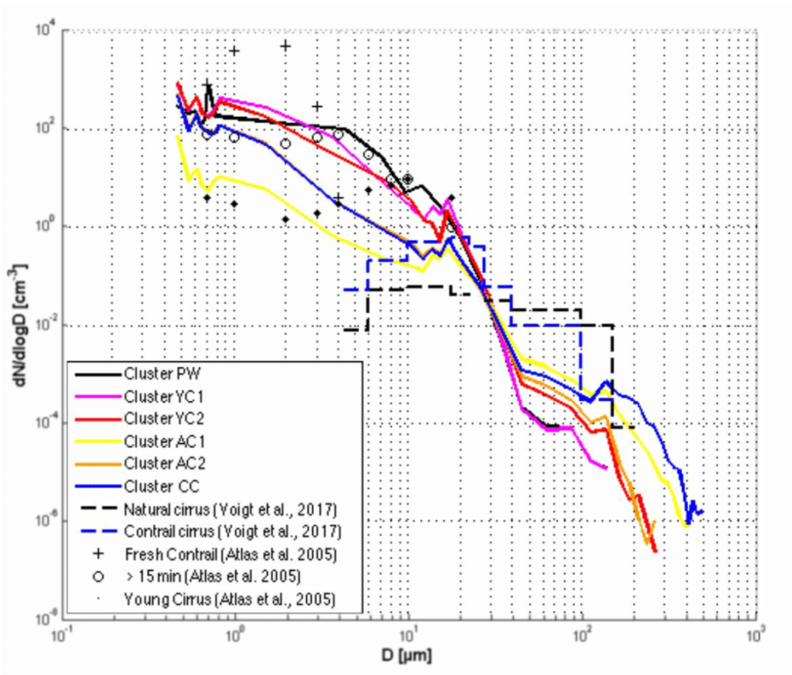

Figure 7: Number particle size distributions for each cluster including all data points of all flights. FSSP-300 measurements from 0.5 to 17 µm and 2DC measurements from 70 µm to 800 µm. The data are linearly interpolated in logarithm space between 17 µm and 70µm.

Voigt et al. (2017) and Atlas et al. (2005) PSD measurements have been added to Figure 7 to get a better picture of previous results. It should strengthen the statements on contrail properties discussed in this section.

l.591:"*Because of this gap, the derived microphysical properties should be considered with caution, but may be used to check the cluster definitions.*"

l. 595: "*Previous studies show that a 3-hours old contrail cirrus with an effective diameter close to 20 µm (Voigt et al., 2017) and number concentration larger than 0.1cm*$^{-3}$ *(Schumann et al., 2017) can be composed of ice crystals with sizes up to 100 µm (blue dashed line, contrail cirrus figure 7). This differs from the PSD of the natural cirrus presented by Voigt et al. (2017) (dashed black line), which has an order of magnitude lower particle number concentration. In natural cirrus at mid-latitudes, ice crystals with size up to 1600 µm were observed during the ML-CIRRUS campaign (dark dashed line Figure 7, Voigt et al., 2017).*"

l.630: "*These properties are in agreement with previous measurement reported by Gayet et al. (2012) with particle number concentrations close to 200 cm*$^{-3}$ *for contrails less than 60 s after their formation. Their work also reports extinction coefficient around 7 km*$^{-1}$ *presenting the highest values of the contrail life time.*"

l.638: "*The ice number concentrations are in agreement with previous results with values between 200 and 100 cm*$^{-3}$ *for contrail ages between 60 s and 3 min, and around 5 cm*$^{-3}$ *for contrail ages around 10 min (Goodman et al., 1998 ; Lawson et al., 1998 ; Schröder et al., 2000 ; Schäuble et al., 2009 ; Gayet et al., 2012 ; Voigt et al., 2017).*"

l.645: "*However, the ice number concentration and the extinction coefficient are higher than in previous studies, with values around 0.1 cm*$^{-3}$ *and 0.023 km*$^{-1}$ *respectively*."

Line 223-225: You aren't using the 2DC for calculating IWC though! I don't see why this sentence is needed. However, I think text here justifying why you are not using observations below 70 microns due to the 2DC's limited response time and depth of field need to be here.

Optical and microphysical properties of contrail particles cannot be fully retrieved without the 2DC measurements. In the present study, these properties are retrieved with both instruments FSSP and 2DC, to consider as much as possible the full size range of the particle size distribution. A linear interpolation has been applied between the two instrument ranges. The text has been clarified according to this remark.

Modification:
l.191: "*Particle size distributions and corresponding microphysical and optical integrated properties (IWC, Deff, N, and extinction) were derived from both FSSP-300 and 2DC measurements.*"

Section 3.2: I think more justification needs to be given for the choice of your feature space for the PCA, since right now it is presented without really linking the feature space to looking for quantities that we expect to vary in differing stages of contrail cirrus. For example, why did you conduct a PCA on the entire scattering phase function instead of just apply clustering to the asymmetry parameter?

Also, why were the clusters manually chosen instead of using automated techniques like k-means clustering?

We thank the referee for this very interesting point and for the new perspective brought to the interpretation of our results. The k-mean clustering method was applied to our dataset. We found that this clustering method lead to an accurate (and more robust) classification of every contrail phase and natural cirrus which agrees with ATC information.
The asymmetry parameter information is not sufficient to define the different clusters (Jourdan et al., 2010). Indeed, gPN information cannot be used to separate the group YC1/YC1 and AC1/AC2/CC, which represent the most interesting part of the study. Additionally, Jourdan et al. 2010 and 2003 showed that the asymmetry parameter alone cannot represent or mimic the variability of the phase function. Indeed, the information content of a phase function measurement can be used to discriminate ice clouds characterized by different ice crystal shape, size or degree of surface roughness which is not the case with the g factor alone. Our study here clearly shows that the first 2 principal components (which are correlated to the extinction coefficient and the g factor respectively) cannot reproduce the whole variability of the optical (and microphysical) properties. The third principal component adds additional valuable information on contrail type which is not directly related to the asymmetry parameter.

Modifications:
The k-mean method has been applied to the dataset and an additional subsection has been added ("*3,2,2 Clustering analyses*). The new clusters are thus defined as mentioned above.

Lines 505-512: How do you know that you flew in an aged contrail with no verification from ATC? I think the important conclusion here is more that, microphysically, aged contrails and cirrus are very similar and are difficult to distinguish with this data alone.

For flight 17 of CONCERT 2, ATC reports chasing but without any possibility to check which aircraft is actually followed. This information indicates that measurements may correspond to very aged contrails or natural cirrus. From in-situ measurements, aged contrails and natural cirrus are very similar. In our case, the PCA method along with K-mean clustering method classifies the 17 C-2 measurement in both aged contrail and natural cirrus (AC1 and CC) with both a significant number of point. This can be explained by a limitation of the method to separate aged contrail and natural cirrus due to quite similar optical properties, but also by a mixture of both natural cirrus and aged contrails. Indeed, differences exist in the [60°-80°] range as well as in the forward and backward scattering regions. These differences can be significant as they are detected by the PCA and the clustering method.

Modifications:
l.505: "*Still ATC data indicate measurements in exhaust plumes and the Falcon flew apparently in visible contrails (ExtPN > 0.1 km^{-1}) which were probably too old for ATC recognition.*"

Line 518-522: I think this analysis can be better supported by showing the distributions of contrail ages from ATC.

Only an estimation of contrail age range is available. We couldn't derive a precise age for each individual contrail sampled during each flights. Table 2 shows the available age ranges for the identified contrails.

Line 593-595: I would not interpolate data in this range since the interpretation of extrapolated data could be quite dangerous. I would simply state that concentrations in this size range are too uncertain to report due to the 2DC's poorly characterized depth of field and response time.

We agree with this comment as the interpolation between the two instruments can induce large uncertainties when calculating the microphysical properties. However, we choose to keep this approximation in order to retrieve microphysical properties comparable to previous studies.

Modifications:
l.623: "*Despite the large uncertainties associated to both instruments and the interpolation between 17 µm and 70 µm diameters, these results again show that each cluster can be connected to a specific contrail phase, and their properties can be compared to previous studies.*"

Lines 607-610: Your YC1 contrails seem to have roughly similar 2DC number concentrations to the aged contrails. Why is that?

The new clustering method refined the cluster definition. Consequently, it leads to a better partitioning of contrail microphysical properties. Indeed, as shown by the new Figure 7, the mean PSD from cluster YC1 displays significantly less particle in the 2DC measurement size range than the one corresponding to AC1 and AC2 clusters.
As already discussed into the text, differences between each mean PSD should be taken carefully due to uncertainties of both probes.

Modifications:
These discussion has been added into the text l.616:"*Within the 2DC range, the PSDs are also in agreement with the cluster definitions. A higher concentration of large ice crystals with diameters around 100 µm and larger are expected for natural cirrus (cluster CC) and for significantly well-developed contrails. This is particularly well illustrated by the mean PSD from cluster YC1 that*

displays significantly less particles in the 2DC measurements size range than the one corresponding to AC1 and AC2."

Lines 640-667: I would convert this into a bulleted list of conclusions to make this paragraph easier to read.

A summary of contrail property is more clearly presented in two separate paragraphs on the conclusion.

Figures/Tables:

Figures 5c,d: A logarithmic x-axis would make the lines easier to distinguish.
Figure 6: I would advise removing the lines where you don't have the PSD from the two probes in the ~20 to 70 micron range. Can you also add size distributions from past studies and include them in the comparison?

Table 2: I think some data from contrails sampled in past studies should be shown and compared against here and in the paragraph discussing Table 2.

Figure 6 c,d : The suggested modifications have been taken into account.

Figure 7: Previous PSDs (Voigt et al., 2017 and Atlas et al., 2005) have been added to the Figure as reported in previous comments of the reviewer. However, we believe that interpolation illustrations at this stage of the paper is essential in order to understand microphysical properties retrieved from this approximation.

Table 3: Results from past studies are now discussed in the text.