

## Reply to Reviewer #1

(Interactive comment on Atmos. Chem. Phys. Discuss., <https://doi.org/10.5194/acp-2022-584>)

We thank the Reviewer for the time she or he spent on the manuscript. The comments helped to improve the manuscript. In the following, the Reviewer's comments and the corresponding responses are listed. The page and line references given by the Reviewer relate to the manuscript in discussion. Numbers given from our side relate to the revised manuscript.

For better legibility, the Reviewer's comments are highlighted in **bold** and changes in the manuscript are in *italic*.

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## Major Comments

**[Sections 4.1 and 4.4] Are these results (i.e., ISSR properties, potential contrail formation, and their respective seasonal variabilities) consistent with existing publications that used radiosonde measurements and in-situ water-vapour measurements from aircraft1–3? It would be great if the authors can compare and quantify the differences in their results relative to existing studies and include a short discussion on the potential reasons causing these discrepancies.**

This comment is helpful. Including previous studies and their analysis helps to set the results of this study in the scientific context. Therefore, the paragraphs in sections 4.1 and 4.4 were extended.

*Generally lower frequencies of occurrence are detected for R2-PC conditions (PC, blue curve) with peak values of 33% during summer and 24% in spring. Autumn is characterized by an intermediate peak probability of 31% and for winter a maximum of around 28 % is identified. The annual cycle in R2-PC conditions is less pronounced compared to the R1-NPC conditions. The largest vertically-integrated occurrence is in winter followed by spring, autumn, and summer, similarly to R1-NPC conditions. This is comparable to Petzold et al. (2020) who analyzed 5 years of Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft (MOZAIC Marengo et al., 1998) observations. Petzold et al. (2020) found a minimum in ISSR, a prerequisite for R2-PC, of 20 % to 30 % in summer and 35 % to 40 % in winter. Nevertheless, Petzold et al. (2020) observed a stronger seasonal dependency compared to our analysis. In contrast, much lower occurrences were found by Rädcl and Shine (2007), with only 10 % of the winter profiles and 17 % of the summer profiles containing R2-PC conditions. The difference between our study and Rädcl and Shine (2007) might be explained by the filtering of the radiosonde data. Rädcl and Shine (2007) used only measurements below the tropopause and rejected profiles with RH<sub>liq</sub> larger than 90 % to remove conditions with iced sensors. The filtering might bias the results towards lower RH profiles. Even lower frequency of occurrence are given for by a recent paper from Agarwal et al. (2022), who found R2-PC conditions in only 3 % to 6 % of the profiles launched between 30N and 60N. The vertical position of the peaks of the R2-PC conditions are located between 10 and 11.5 km, which is around one kilometer higher compared to Rädcl and Shine (2007), who estimated the mean altitude of ISSR between 9.5 and 10 km in winter and summer, respectively. Similar altitudes like in the present paper are reported by Agarwal et al. (2022), with around 9 km in winter and 11 km in summer.*

[...]

*The vertically integrated values of contrail-weighted R2-PC occurrence ranges between 15 % and 22 %. This is significantly higher compared to Agarwal et al. (2022), who identified only 3% to 5 % of the fuel-burn weighted profiles as suitable for persistent contrails. Potential explanations for the differences are the data-sets for weighting the profiles and the overall lower occurrence of PC in the Agarwal et al. (2022) analysis. The differences in frequency of occurrence and mean altitude of R2-PC conditions between this study, Petzold et al. (2020), and Agarwal et al. (2022) likely result from the deviating sampling regions. While the present study uses radiosondes from one station, Petzold et al. (2020) uses observations that cover Europe, the North Atlantic, and North America, and Agarwal et al. (2022) uses selected radiosonde observations between 30° N and 60°N. Furthermore, the reliability and accuracy of radiosonde observations near and above the tropopause are difficult and require careful post-processing. The methods and filtering during the post-processing process can influence the results and explain the differences among our analysis, Rädcl and Shine (2007), and Agarwal et al. (2022).*

**[Section 4.6] The authors estimate the change in the non-persistent and persistent contrail formation from different fuel types. However, as pointed out, these fuels have differences in the water vapour emissions index and nvPM number emissions index, both of which are expected to change the various contrail properties such as the lifetime and radiative forcing4–6. While I understand that the changes in contrail properties are beyond the scope of this study, it would still be appropriate to add a short discussion on the potential changes in contrail properties due to the use of different fuel types.**

The Reviewer is right and points out an important topic. The following paragraph was added to Section 4.6 to highlight the dependence of contrail formation and contrail properties on the amount of emitted soot particles, as the soot particle number concentration is likely to decrease when switching to alternative fuels like hydrogen.

*In the previous analysis one important aspect of contrail and cirrus formation is neglected. Switching to alternative fuel types is accompanied with a suggested reduction of the soot particle number concentration in the exhaust plume and the number of available ice condensation nuclei. Kärcher (2018) showed that for soot-rich regimes ( $N \approx 10^{14} - 10^{16} \text{ kg}^{-1}$ ), an increase in the particle number concentration leads to a linear increase in the number of activated ice crystals. Unexpectedly, a transition to a soot-poor regime ( $N \approx 10^{12} - 10^{14} \text{ kg}^{-1}$ ) leads to an increase of activated ice condensation particles. The increase in the soot-poor regime is explained by the formation and activation of aqueous particles, which subsequently freeze, when the ambient air is sufficiently cold and humid (Kärcher, 2018). Case studies from Kärcher et al. (2015); Kärcher and Voigt (2017) as well as measurements from Moore et al. (2017) and Voigt et al. (2021) provide support to the model from Kärcher (2018) although there remain large uncertainties. In addition, a recent study by Bier et al. (2022) showed that switching to bio-fuels also modifies the size of the ice particles, which further modifies the optical properties, hence the radiative forcing, and the contrail life-time.*

**[Section 4.7] The results in this section were very well described. However, the authors can improve it further by highlighting the potential factors that contribute to the seasonal difference in flight altitude changes in minimising persistent contrail formation. For example, it would be great if these results can be related to the seasonal cycle of the thermal tropopause height, as illustrated in Figure 5.**

Following the suggestion of the Reviewer, an additional paragraph was added to provide a link between the annual cycle of R2-PC conditions and the flight altitude deviations.

*As shown in Fig. 5 the region for R2-PC is subject to an annual cycle, which is highest in summer and lowest during the winter month. In summer the overlap with today's FAD is largest, with the median of R2-PC and FAD at similar altitude. Therefore, flying at higher or lower altitudes reduces the vertically integrated chance for R2-PC formation. During the winter months, when the R2-PC is generally lower, a shift to higher flight altitudes reduces the overlap. Similarly, the lower median altitude of R2-PC during winter explains why higher cruising altitudes reduce the vertically integrated chance for R2-PC.*

#### **Minor Comments**

**[Line 43] It would be great to add a short sentence describing the second-order effects of contrails in affecting the natural cirrus properties<sup>7,8</sup>.**

We thank the Reviewer for pointing this out. This is an important factor with respect to the total cloud cover at cirrus altitude. Accordingly, the paragraph was extended.

*However, it is still unclear to which extent contrails alter the occurrence of natural cirrus. Contrails modify the water vapor budget around them, leading to a competition for available water vapor supersaturation through condensation on ice particles (Ponater et al., 2021). This can lead to reduced natural cloud cover, a change of cloud optical properties, as well as the lifetime of natural cirrus (Burkhardt and Kärcher, 2011; Ponater et al., 2021).*

**[Line 53] The terms “terrestrial RF” and “solar RF” that were used in this paper are not commonly used in the literature. The authors can consider renaming them to “shortwave (SW)” and “longwave (LW)” RF here and in other parts of the paper to conform to the terminology that is used in the literature.**

Following the suggestion from the Reviewer, the terms “terrestrial” and “solar” are exchanged for “longwave” and “shortwave”, respectively. The changes are not copied into this reply but we direct the Reviewer to the difference file of the manuscript.

**[Line 272] There is a typo where “R1-NOC” should be “R1-NPC”.**

The typo is corrected and ‘R1-NOC’ is replaced by ‘R1-NPC’ .

**[Lines 430 - 432] This statement conflicts with Figure 5c. The stratosphere is generally dry and identified where the background H<sub>2</sub>O is below 10 ppm. Ice supersaturation in the stratosphere is a rare event and Figure 5c shows that persistent contrails generally form below the troposphere.**

We partly agree with the comment of the Reviewer and rephrased the section of the text, highlighting that supersaturation in the lower stratosphere is a rare event. Nevertheless, such events have been observed[1]. Furthermore, multiple definitions for troposphere and stratosphere exist. The one mentioned by the Reviewer refers to the definition by water vapor concentration. Alternatively, a definition by temperature is used[2].

*[...]Furthermore, flying higher may have other drawbacks, especially if the fraction of flights cruising in the stratosphere increases. Emission of water vapor in the lower stratosphere has a stronger radiative effect compared to emissions in the tropopause. In addition, Gierens et al. (1999) found that, on some occasions, supersaturation can be present in the lower most part of the stratosphere and contrails that form in the lower stratosphere may have a longer life-time given the larger stratification compared to the troposphere (Gierens et al., 1999; Irvine et al., 2012). While supersaturation in the stratosphere might be rare, the increase in total flights in the lower stratosphere combined with the extended life-time can lead to an increased contrail coverage. It is also important to recognize that these results may not generalize to other sites and to other latitudes. A similar study would be needed with a much larger set of RS locations before robust conclusions can be reached. [...]*

**[Lines 477 – 485] It would be a great for the authors to highlight that the contrail climate forcing from NPC are generally negligible, and that PC's are the significant contributor to contrail climate forcing.**

The Reviewer is right and this is an important comment to interpret the results and to give advice on which contrail type should be avoided. The following text was added to the paragraph to highlight the importance of PC mitigation.

*It has to be emphasized that the primary objective is to minimize or entirely avoid PC as they are suspected to cause the major fraction of contrail related radiative forcing, while the effect of NPC is almost negligible (Kärcher, 2018; Teoh et al., 2020a).*

[1] (Gierens et al., A distribution law for relative humidity in the upper troposphere and lower stratosphere derived from three years of MOZAIC measurements, 1999, Ann. Geophys. , Vol. 17, No. 9, p. 1218-1226)

[2] (Petzold et al., 2020, Ice-supersaturated air masses in the northern mid-latitudes from regular in situ observations by passenger aircraft: vertical distribution, seasonality and tropospheric fingerprint, 2020, Atmos. Chem. Phys. , Vol. 20, No. 13, p. 8157-8179)