Reply to Community Comment #1 (Dennis Piontek and Ulrich Schumann) (Community comment on “Radiative effect by cirrus cloud and contrails – A comprehensive sensitivity study” by Kevin Wolf et al., EGUsphere, https://doi.org/10.5194/egusphere-2023-155-CC1, 2023)

We thank Dennis Piontek and Ulrich Schumann for the time they spent on the manuscript. The comments helped to improve the manuscript, but more importantly spurred us into repeating our calculations with (1) a completely revised libradtran configuration to ensure that we use state-of-the-art parametrization; and (2) much extended parameter ranges to be better representative of cirrus and contrails. The discussion in the manuscript has been revised to reflect the new calculations and analyses. 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 Community Comments are highlighted in bold and changes in the manuscript are in italic.

The study of the radiative forcing of cirrus and contrails is an important task. In particular the climate impact of contrails gets significant attention in the past years as the avoidance of contrails by next- generation aircraft engines, the rerouting of flights, and the use of sustainable aviation fuels promises to be an easily achievable climate change mitigation strategy. In that sense, we want to applaud the authors for contributing to this endeavor.

The authors present an ambitious study to evaluate the radiative forcing due to ice clouds by performing a large number of radiative transfer calculations (94,000) for different atmospheres, liquid water and ice cloud configurations (I.e., different optical depths and heights), ice crystal sizes and shapes, surface temperatures and albedos, as well as solar zenith angles. The radiative impacts in the thermal infrared and the solar spectrum are quantified. For the calculations, the established radiative transfer code libRadtran (Mayer & Kylling, 2005) was used.

As the authors pointed out, various studies already investigated the cloud radiative forcing with different foci. However, we agree to the third reviewer: the statement in lines 70-71 (most “comprehensive sensitivity study”) needs further work to become fully justified. One comparable but missing study is “A Parametric Radiative Forcing Model for Contrail Cirrus” by Schumann et al. (2012a). In this study, libRadtran was used as well to simulate the thermal and solar cloud radiative forcing of contrails, covering different surface and atmospheric conditions, solar zenith angles, seven different ice particle shapes and effective particle radii up to 45 µm, different liquid and ice water configurations. In total, 36,576 calculations were performed. Based on this dataset, approximations of the long- and shortwave radiative forcing due to contrails were derived. The study also shows sensitivity studies with respect to various quantities (e.g., contrail optical depth, solar zenith angle, effective albedo).

Due to the strong similarity of the simulated datasets of Wolf et al. And Schumann et al., it appears mandatory to perform a direct comparison. Thus, we compared in a quick first study the calculations of Wolf et al. With the parameterizations developed by Schumann et al. Those are implemented in the Python package pycontrails (https://py.contrails.earth) which includes (among others) the "Contrail Cirrus Prediction Tool" (CoCiP, Schumann, 2012b).

The approximation of the longwave radiative forcing needs 5 inputs, which we estimated by data from Wolf et al. As follows:

Table (see original posting)

The ice crystal habits are considered separately, as the habit is given as an additional parameter to the radiative forcing functions of pycontrails (here, it is mainly used to convert r_vol back to r_eff internally; the parameterization of Schumann et al., 2012a, relies solely on r_eff and is independent of the ice crystal shape). We considered rough aggregates and droxtals. Wolf et al. Also performed calculations for plates. However, the approximate conversion between r_eff and r_vol is non-linear (Schumann et al., 2011); thus, we did not consider plates for the moment.

Note that the cirrus optical depths provided by Wolf et al. And used in the approximation of Schumann et al. (2012a) are for different wavelengths (640 and 550 nm, respectively). However, we assume that the differences in the ice optical properties are in the order of few percent (Lynch & Mazuk, 2001) and, therefore, negligible.

Unfortunately, also the definitions of "top of atmosphere" differ as Wolf et al. Define "top of atmosphere (TOA) at 15 km" height. As a result, the upward thermal infrared irradiance of Wolf et al. Can only be considered as an approximation of the outgoing longwave radiation at top of atmosphere in the sense of Schumann et al. (2012a). This is also visible when considering the downward thermal infrared irradiance of Wolf et al., which is not zero but varies between roughly 7 and 10 W/m². The difference in the definition of top of atmosphere has also an impact on the inputs for the solar direct radiation and the reflected solar radiation, as well as the resulting cloud radiative forcings in the long- and shortwave spectrum.

Nevertheless, we find that the results of Wolf et al. And the approximations of Schumann et al. (2012a) are in reasonable agreement (see plots below), with Pearson correlation coefficients of 0.979 and higher. The longwave radiative forcing based on Schumann et al. (2012a) is slightly smaller than the results of Wolf et al. Towards the lower end of considered thermal infrared radiative forcings. For the shortwave radiative forcing, we find a larger scatter between both results.

Although these results represent only a first quick look into the matter and further investigations might be necessary, the comparison already seems to show that the calculations presented by Wolf et al. (and, thus, the underlying input datasets and assumptions) agree with the work presented by Schumann et al. (2012a).

We thank both authors for this interesting companion. The plots they provided indicate that the parameteriziations and the simulated RE agree, which increases the confidence in our and their results. The increasing differences in ΔF towards smaller cloud optical thickness are explained by the increasing contribution of ambient conditions and the decreasing contribution of the ice cloud itself. Consequently, parameters like the surface albedo or humidity profile, become more influential and important, and lead to deviations and the scattering. However, a detailed comparison between the simulations and the parameterization is beyond the scope of the presented study. A dedicated study, which addresses these differences in detail might be a useful contribution to the literature.

Further major comments to the manuscript:

We appreciate that the results in Wolf et al. Are close to the results in Schumann et al. (2012), but we miss a discussion of a) the variable humidity: It is well known that the relative humidity over ice is often close to 100 % near cirrus and contrails (see Li et al., 2023). But, what is the relative humidity in your profiles?

We have added plots of the temperature and relative humidity profiles used in the calculations to the appendix.

In addition, we have performed an analysis of the sensitivity of our results with respect to the RH profiles. Anderson (1986) states that standard profiles are subject to variations between 10 and 30%. So, we varied the original RH profiles by +/- 20% and repeated the simulations for a sub-set of the total range of simulations. The modified profiles are used to a) account for the potential variation in the profiles and b) to estimate the impact of different RH profiles on simulated solar, TIR, and net radiative effect. Variations in RH did not show an impact on F_{sol} (+/- 0.4%) but modify F_{tir} (+/- 4.1%) and F_{net} (up to +/- 8), particularly the relative values of F_{net}. We did not modify the RH profiles around the cloud, but this could be looked at in a follow-up study.

b) any other absorbing gases or species (O3, CO2, aerosols)?

Temperature and humidity profiles from libRadtran (Emde, 2016) are used, which base on the atmospheric profiles from Anderson, 1986. As already mentioned in the manuscript, molecular absorption is included but now the individual gases that contribute to the absorption are explicitly stated in the manuscript. The atmospheric composition, i.e., concentration of the gases, is also taken from the atmosphere profiles of Anderson, 1986. Absorption by aerosol is not considered in our simulations.

Discussion of importance of large solar zenith angle SZA > 70°: The shortwave radiative forcing reaches a maximum near or above that SZA value, see Figs. 7 and 8 in Schumann et al. (2012), Fig. 12 in Markowicz & Witek (2011), Fig. 1 in Myhre & Stordal (2001); and hence this parameter range is important at sun dawn in early morning/late evening (Meerkötter et al., 1999).

The problem with high SZA is, however, that clouds in general, and contrail cirrus clouds in particular, can only very roughly be approximated as horizontally homogenous, in particular when the sun is low over the horizon. We miss a study on the 3d-effects of contrails (depending among others on SZA, azimuth of contrail-line direction relative to the sun, on the width/thickness ratio of the contrails lines (Forster et al., 2014), besides the 3d clouds in the contrail neighborhood), besides the effects of

non-spherical Earth geometry and solar radiation refraction in the atmosphere at high SZA.

The Reviewers raise an important point. Following the suggestion and the provided literature, we extended the range of simulated SZA to 85º. Based on these additional simulations, we added a paragraph to the manuscript, in which we discusses the sensitivity of solar ΔF on SZA and link the discussion with the provided literature.

We chose a maximum SZA of 85º because the radiative transfer solver "DISORT" treats atmospheric layers as plane-parallel. Results for θ > 85º are likely nonphysical and have to be treated with caution (Stamnes, 2000; Buras, 2011). In addition, the biases between 1D and 3D simulations increase with SZA and are now highlights in the introduction of the manuscript.

With respect to your Appendix B: In Schumann et al. (2012), Bernhard Mayer noted: "the irradiances are computed using the discrete ordinate solver by Stamnes et al. (1998), version 2.0, with six streams, which allows accurate simulations of irradiances." We wonder why you need 16 streams and cannot calculate at high SZA? Do you want to say that the former results are significantly inaccurate for methodological reasons? We expect small differences between 6 and 16 streams.

and

The test example assumes a surface albedo of one and liquid water clouds below the ice clouds. Hence the solar forcing is small in this case. Is this the best test case?

The choice of 16 streams comes from a compromise between computational time accuracy. We found a small, worthwhile gain in accuracy when increasing the number of streams from 8 and 16. Adding more streams provides only negligible additional accuracy. The presented plot D1 in the appendix shows only one exemplary cloud scenario.

The case was selected to have a significant fraction of upward irradiance (contribution from the surface) plus adding the interaction of a liquid water cloud. The aim was to create a profile with cloud-surface-cloud-radiation interaction. The selected example might not be the ideal case and, therefore, the conservative approach with 16 streams is used.

The manuscript has not been changed in this regard.

Why do you use the older Fortran version of libRadtran? The more stable C-Version is available since 2010.

This is an important comment. We switched to the DISORT solver and repeated the simulations.

Another important issue, which is so far only approximately covered, is the effect of overlapping contrail cirrus clouds. We found (see Schumann, Poll et al., 2021) that Europe is covered frequently by very many contrails which get wide compared to the lateral distances to other contrails so that they partially overlap each other and so that contrails forming above or below the first contrails experience a changed radiation field with different effective OLR/RSR values. We used a rough approximation to

account for this effect and found that it changes the computed net RF by a factor of order two over Central Europe, depending on air traffic density and humidity.

In a recent study by Sanz-Morère et al. (2021) it is reported that contrail-contrail radiative effects can likely be neglected in estimates of the radiative effect. Furthermore, adding a second ice cloud / contrail to the simulations would add another dimension in the multi-dimensional simulation set-up. Here we wanted to focus on the basic dependencies.

> *"The parameter selection of this sensitivity study was motivated by Meerkötter et al. (1999), which was supported by previous studies, for example Fu and Liou (1993), Zhang et al. (1999), Yang et al. (2010), or Mitchell et al. (2011). Schumann et al. (2012) then parameterized the effects of the parameters identified by Meerkötter et al. (1999) on the cloud RE. Additional influences like aerosol layers, more complex surface albedo, or multiple overlapping cirrus and contrails have not been investigated here and represent additional degrees of freedom. For example, previous studies found that aerosols have only a minor influence on contrail RE (Meerkötter et al., 1999) and Sanz-Morère et al. (2021) reported that the impact of overlap between contrails on their RE is negligible. Nevertheless, the present study covers the parameters that most directly affect cirrus RE."*

Line 192, Eq. 11: Why do you need the factor β? The r_vol is defined with β = 1 for arbitrary habits, see Schumann et al. (2011), Eq. 18, at least for fixed ice density ρice . More important (besides ρice for porous crystals), is the ratio C=r_vol/r_eff, see Eq. 1 in the same paper. Do your results change and how much if you use β = 1 consistently in your study?

Due to this and other Reviewer comments, the set of equations have been revised in the updated manuscript. A more accurate mass-size relationship if provided in the manuscript following Mitchel (2002). We direct the authors to the diff file and see section 2.2.

Minor comments to the manuscript:

Why do you use the term "Radiative Effect, RE"? We think that the term "Radiative Forcing RF" is more often used. What is the difference between RE and RF?

Although the terms radiative forcing and radiative effect are often used interchangeably in the literature, they have different meanings. Cloud radiative effect is the contribution of clouds to the Earth's radiative budget. Radiative forcing means a change in radiative effect since pre-industrial conditions. In the case of contrails, which were not present in the atmosphere in pre-industrial conditions, radiative effect and forcing are equal. But that is not true in general, which is why we use the term "effect".

Line 32: We do not understand why you cite Jensen et al. (1994) here: "contrails are short lived and can persist...". Jensen et al. Discuss tropical cirrus, not contrails. Here the paper by Schumann (1996), even if not the first (see also Schumann, 1994, and Busen & Schumann, 1995) is often cited as the most comprehensive introduction of

contrails in literature at least until that time (see also Schumann & Heymsfield, 2017a, besides Kärcher, 2018).

Agreed. The citation from Jensen (1994) was removed and references from Schumann (1994), Schumann (2017), and Kärcher (2018) were added.

Line 35: Regarding the importance of cirrus cloud cover and contrails over Europe, you may also refer to Schumann, Penner et al. (2015) and Schumann, Bugliaro et al. (2021).

This is correct and we added these two references to the text in line 35.

Line 36: The fact that shortwave radiative forcing is mostly negative is well known. It should be mentioned that it can be positive for high surface albedo and high absorption in the atmosphere between ground and cirrus cloud as discussed in Meerkötter et al. (1999), page 1089, right column. See also Myhre & Stordal (2001), Fig. 1 (but published without explicit explanation).

This is an important point. Nevertheless, the sentence is meant as a general introduction here with the emphasis on 'most of the cases'. Nevertheless, we value the suggestion and include the two citations later in the manuscript, where the influence of a high surface on the cirrus / contrail radiative effect is discussed.

Line 137: Presumably the most comprehensive collection of aircraft in-situ and remote sensing measurements of contrail properties can be found in Schumann, Baumann et al. (2017b) and in the therein described open-access contrail library "COLI"; they cover not only young but also the more important aged contrails (partially exceeding 10,000 s).

We thank the Reviewers for providing this citation. It was added to the manuscript to provide guidance for the interested reader.

Line 158, Eq. 7 to 9: Very similar equations can be found in Schumann et al (2011).

We find it strange that you cite Meerkötter et al. (1999) in the figure caption of Fig. 2, but do not discuss similarities or disagreements in the content in the text. In fact, we still have to identify any basic new information in your discussion of Fig. 2.

We adopted the excellent Figure design of Meerkötter et al. (1999) for Figure 2 to provide a good introduction for the more detailed investigation of the individual parameters. The intention is not to compare to their results. We included a paragraph that describes the intention behind the Figure in the manuscript.

> *"The presented analysis of solar, TIR, and net ΔF sensitivity on the selected input parameters generally agrees with the results from Meerkötter et al. (1999). We found differences in the importance of the parameters, which are explained by the fact that*

our simulations span a larger and different parameter range, for example in r_{eff} and T_{srf} . In addition, the sensitivity analysis in Fig. 2 is sensitive to the selection of the reference cloud."

The discussion of r_{eff} and IWC as the most important parameter is incomplete and partially misleading (at many places and in particular in section 3.3 and in the summary, line 499). Physically, the most important parameter is the optical depth τ of the contrail cirrus, which is, among others, a function of r_eff, IWC and cloud geometrical thickness D. The r_eff is a secondary factor besides crystal habit etc. Of course, IWC, r_eff, D and crystal habits are important per se and possibly easier to measure while models might primarily compute the IWC and then estimate crystal habit and optical extinction βext for given IWC and temperature (Heymsfield et al., 2014), but τ ~ βext D, by definition, is the parameter which characterizes the impact of a cloud layer on radiation transfer.

We partly agree with this comment. In our opinion, clouds can be regarded from two different perspectives: microphysical properties and optical properties. In this paper we follow the microphysical perspective, based on properties like ice water content and the ice particle size distribution / r_{eff}. As the comment states, cloud optical thickness is then a function of IWC, r_{eff}, cloud geometric thickness, and particle shape.

The discussion of the importance of the surface temperature is misleading. It is not the surface temperature that is important but the effective brightness temperature of the atmosphere below the contrail cirrus, which in fact depends not only on the surface temperature but also on water vapor and other IR absorber profiles and low level clouds, besides spectral averaging. It was exactly this reason why Schumann et al. (2012a) parameterized the longwave radiative forcing not as a function of surface temperature (as also done by Corti & Peter, 2009), but as a function of OLR without contrail cirrus.

We acknowledge the fact that the surface temperature does not alone determines the forcing of a cirrus but the entire atmosphere between surface and the cirrus as a whole. However, we use the surface temperature as a proxy for a certain temperature- and humidity profile to represent three different regions on the Earth. In the revised version of the manuscript, particularly in Section 3.5 and Appendix B, we better highlight the coupling of surface temperature and related atmosphere profiles of temperature and humidity.

In summary, we highly appreciate that this study was performed and that we got access to the data, since this gives us the chance to test our parameterizations, but the paper needs considerable extensions and improvements before it can be published as a "comprehensive" study.

We would like to answer this comment similar to Reviewer 3.
Claiming to provide a 'comprehensive' study is misleading. Following the suggestion of the Reviewer we rephrased the objective of this study and removed 'comprehensive' from the title

and the manuscript. Nevertheless, the main objective remains, which is to identify the main drivers of the cirrus RE among the eight selected parameters.

The selection of the parameters primarily based on the study performed by Meerkötter et al. (1999), which was supported, e.g., by Fu and Liou (1993) as well as Yang et al. (2010), who focused on the effects ce crystal habit and the ice water path. The effect of the ice crystal size distribution was analyzed, for example, by Zhang et al. (1999) or Mitchell et al. (2011).

Later on, Schumann et al (2012) parameterized the cloud radiative effect in dependence of the parameters identified by Meerkötter et al. (1999). We take a slightly different approach compared to Schumann et al (2012) and regard the cloud radiative effect of clouds from a microphysical perspective instead of an optical perspective. In addition, we provide an update of the calculations from Meerkötter et al. (1999) by using up-to-date radiative transfer models in combination with the latest cloud optical properties.

Furthermore, we strive to identify the driving parameters of RE by sampling the input parameter range, restricted to values that are typically associated with ice clouds. Finally, we attempt to provide an open-access data set, which allows the user to extract cloud REs for user-specific combinations of the input parameters. The data set might be coupled with cloud microphysical models, e.g, the Contrail Cirrus Prediction Tool (CoCiP) from Schumann (2012), to estimate the cloud radiative effect of the simulated contrails.