Reply to Reviewer #3

(Referee 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-RC3, 2023)

We thank the Reviewer for the time she/he 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 Reviewer's comments are highlighted in **bold** and changes in the manuscript are in *italic*.

This study presents a dataset of radiative transfer simulations with the goal to investigate the sensitivity of the radiative effect of cirrus and contrails. The sensitivity study comprises eight selected parameters: ice crystal effective radius, ice water content, solar zenith angle, surface albedo, liquid water cloud optical thickness of an underlying cloud, three ice crystal shapes, cirrus temperature, and surface temperature. The dataset which is submitted together with the manuscript consists of three netCDF files, one for each ice crystal shape. Results for plane-parallel radiative transfer simulations are provided as upward and downward irradiance for cloudy and clearsky scenes as well as the cloud radiative effect (CRE), integrated over the solar and thermal spectrum. While such a sensitivity study has the potential to provide interesting insights into the driving parameters on CRE of cirrus and the associated data set is useful as a reference, there are a number of major issues which have to be addressed before publication:

(A) The manuscript is missing a discussion of the results and comparison with previous studies which are mentioned in the introduction (Fu and Liou (1993), Yang et al. 2010, Zhang et al. 1999, Mitchell et al. 2011, and Schumann 2012). Are there new insights gained from the selected parameter space?

We thank the Reviewer for providing these literature. During the revision of the manuscript the cited literature was consulted and compared to our results. We would like to direct the Reviewer to the diff file as the corrections have been made in multiple sections of the manuscript.

(B) There are several major issues with the setup of the RT simulations which have to be addressed, especially since the data set is intended for public use:

1. **Top of the atmosphere (TOA) is assumed here at 15 km (as stated e.g. in line 90 and Table 1) instead of the commonly used 120 km (Emde et al. 2016). All atmospheric profiles provided in libRadtran and used in this study are defined up to 120 km. The upward and downward irradiances computed in this study are therefore missing important contributions of molecular scattering and absorption. To allow comparison with other studies and make the data set useful for the community, irradiances should be computed at the standard TOA level.**

   We follow the suggestion of the Reviewer and set the uppermost level to 120 km. The simulations have been repeated and the manuscript has been revised accordingly. Please see the diff file.

2. **Ice cloud optical thickness values are provided for a reference wavelength of 640 nm. The standard reference wavelength, however is 550 nm. Similar as above, to allow comparison with other studies and make the data set useful for the community please use 550 nm as a reference wavelength.**

   We follow the suggestion of the Reviewer and provide the output at 550 nm wavelength. The simulations have been repeated and the manuscript has been revised. Please see the diff file.

3. **The study claims to use the “more recent ice crystal parameterizations” (line 61) but only droxtals were used from Yang et al. 2013, whereas Yang et al. 2000 was used for plates and rough aggregates. Yang et al. 2013 provides optical properties for plates and rough aggregate as well. Why not use the latest optical properties in a consistent way?**

   The Reviewer is right. For consistency and for the sake of using ‘more recent ice crystal parameterizations’, we have remade all simulations, now using the ice optical properties from Yang (2013).

4. **Furthermore, no explanation or discussion is provided why these specific habits were chosen. Why are e.g. columns or bullet rosettes not included? Please provide motivation to select “droxtal”, “rough-aggregates” and “plates” and cite relevant literature that supports this choice as representative for cirrus, contrails, and contrail cirrus (e.g. Platnick et al. 2016, Forster et al. 2022, Järvinen et al. 2018).**

   The Reviewer highlights an important point. Item four in section 2.2 about the selected ice crystal shapes is greatly extended. Following the suggested literature it shows that rough aggregates are most commonly detected in cirrus clouds. The observations include LIDAR observations form satellite, aircraft in-situ observations, and ground-based observations. This is now mentioned in the text and supported by the suggested literature. Please see the diff file for the extended text.

5. **It is not explained why libRadtran’s Fortran implementation of DISORT is used for the radiative transfer simulations instead of the faster and more robust C-version (Emde et al. 2016), when the goal is to use the “latest RT models” (line 62).**

   We thank the Reviewer for the helpful suggestion to use the DISORT solver. The solver has now been used to repeat all simulations.

6. **The results including the water cloud below the cirrus are potentially biased: “wc_modify tau set 20” in the input file will set the water cloud optical thickness to 20 at each wavelength which causes the liquid water content to vary across the spectrum. To achieve constant LWC, it has to be be scaled directly to an optical thickness of 20 at 550 nm wavelength.**

   We thank the Reviewer for this remark. All new simulations use ‘wc_modify tau550 set xx’ to scale the cloud optical thickness at 550 nm wavelength.

7. **The water cloud layer is fixed with cloud base at 3 km. This implies that the cloud layer is located at a different temperature for each of the 3 atmospheric profiles. As stated in the manuscript (line 174) this places the cloud even at temperatures below freezing for the subarctic winter profile. To be consistent, should the water cloud not rather be fixed at a certain temperature, the same way the altitude of the ice cloud was defined?**

   Within the subarctic winter profile all temperature values are below freezing. This implies that all potential clouds, positioned in this profile, will be below freezing and, in case of liquid clouds, contain super-cooled droplets. Nevertheless, clouds with super-cooled droplets at cloud top are frequently observed (70% of the clouds) in the arctic (e.g., Hogan 2004 and Hu 2010).
   In the simulations the liquid water cloud is positioned at a fixed cloud top altitude of 1.5 km and a geometric thickness of 0.5 km. In all three atmospheres (sub-arctic, mid latitude, and tropics) low-level clouds at this altitude occur frequently.
   Please see the diff file for the extended item 8 in section 2.2 of the manuscript that explains the positioning of the liquid water cloud.

8. **Information about the setup of the radiative transfer simulations is contradicting in several places in the manuscript, or missing:**

- **It is not explained how the surface temperature is set in the RT simulations. The stated temperatures of 273 K for afglsw and 313 K for afglus do not correspond to the surface level temperature of these atmospheric profiles as provided by Anderson et al. 1986.**

  We agree with the Reviewer. The old selection caused a discontinuity in the temperature profile at the interface between surface and atmosphere profile. The surface temperatures have been changed to agree with the lower most (0 km altitude) temperature of the atmosphere profiles.

- **Molecular absorption is stated to be Fu and Liou (1992, 1993) in Table 1, then the text states REPTRAN parameterization in “moderate” resolution (line 110), and the sample input file provided as a supplement uses REPTRAN in “coarse” resolution. Please double-check and explain the choice.**

  The REPTRAN resolution was double-checked. All new simulations have been run with a ‘coarse’ resolution and the manuscript has been changed accordingly.

  > *The RT simulations consider molecular absorption using the 'coarse' resolution REPTRAN parameterization [...]*

- **In Table 1, and line 109 it is stated that the spectral solar irradiance according to Kurucz 1992 is used. The data provided with libRadtran has a spectral resolution of 1 nm, but the sample input file refers to a version with 5 nm resolution. How was that obtained and why did the authors choose a coarser resolution?**

  Previously, the solar irradiance from Kurucz 1992 was interpolated from the original 1 nm resolution to 5 nm resolution. In the new simulations the original 1 nm file is used.

  (C) A clear statement of the intended use of the dataset together with assumptions made for the radiative transfer simulations and their impact on the accuracy of the results is missing. The abstract (line 21/22) states: “The data set […] can be used to compute the radiative effect of cirrus clouds, contrails, and contrail cirrus instead of full radiative transfer calculations.” This is a very general statement and it is not clear what potential use cases could be. Although it is very useful to publish the results together with the paper, potential users of the data set would need more guidance: Please provide more details how the data set should be used, limitations, accuracy, possible questions that could be answered.

  1. **Important information is missing about assumptions used for the radiative transfer simulations which have important implications for potential use cases: Plane-parallel RT instead of 3D RT, assuming TOA at 15 km, assuming randomly oriented ice crystals, parameterization of ice crystal optical properties which assumes a coupling of crystal size and aspect ratio, constant geometric thickness of the cirrus of 0.2 km, etc.**

     These assumptions are provided more prominently in item 4 in section 2.2 in the manuscript to ensure correct usage of the published data and to raise awareness of potential uncertainties.

  2. **Especially for contrails and contrail-cirrus, but also for cirrus radiative 3D effects have been shown to be non-negligible (e.g. Gounou and Hogan 2007, Kalesse 2009, Forster et al. 2011). If the presented results should be applicable to contrails the bias due to neglecting these 3D effects has to be quantified.**

     The Reviewer highlights an important point. Considering further Reviewer comments, we added a dedicated section that mentions and partly discusses the differences between 1D and 3D simulations and the associated uncertainties. However, a quantification of the differences is beyond the scope of this study. To raise awareness on that potential uncertainty, we provide numbers and citations from the suggested literature: Gounou and Hogan (2007) as well as Forster et al. (2011).

     However, we note that aged and spread contrails might be approximated as homogeneous thin plane-like clouds, which justifies the use of 1D simulations (Minnis et al., 1999).

More detailed comments:

1. **Abstract line 18: Why is TIR influenced more by ice crystal shape than effective radius? In line 298 it is stated that crystal size has a stronger impact than shape. Please explain in the text.**

It is stated in the text that r_{eff} and IWC are the dominating factors in the solar and TIR wavelength range. For TIR the other parameters are given in descending order.

2. **Abstract line 19: "Net RE is controlled by the surface albedo, the solar zenith angle, and the surface albedo in decreasing importance". Surface albedo is mentioned twice, please correct.**

   The Reviewer is right and the sentence has been corrected.

   > *" The combined net RE is controlled by α_{srf}, θ, and T_{srf} , sorted in decreasing importance."*

3. **Line 69-72: "A comprehensive study of cirrus radiative effects was conducted by Schumann (2012), who aimed to derive an approximate model to estimate the cloud RE. While those studies are valuable, none of them presents a comprehensive sensitivity study across all relevant cloud and environmental input parameters. Therefore, we present a study that separates the effect of eight selected parameters on the cirrus RE."**
   This is contradictory: none of the previous studies is "comprehensive", but the present study focuses on "eight selected parameters". Are the eight selected parameters of the present study enough to make it "comprehensive"? Should not the driving question be: How many and which parameters are necessary to investigate the main question / support the main statement?

   The Reviewer is right. 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.

   > *"Multiple studies that aimed to investigate the impact of a certain parameter on cloud RE have been performed in the past. Fu and Liou (1993) as well as Yang et al. (2010) focused on the effects of the selected ice crystal habit and 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). A comprehensive study of cirrus radiative effects was conducted by Schumann (2012), who aimed to derive a parameterization to estimate the cloud RE. While those studies are valuable, none of them investigate the effect of multiple factors, like relevant cloud and environmental input parameters. These studies have identified parameters that affect cirrus RE, but all these parameters need to be considered together, including both cloud and environmental parameters. This article is intended as a parametric sensitivity study that aims to compare the effects of major parameters. Furthermore, we identify the driving parameters of RE by sampling the input parameter range, restricted to values that are typically associated with ice clouds. Finally, we 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 RE of the simulated contrails"*

4. **Line 85: Please add the equation for DeltaF_net before defining DeltaF_sol and DeltaF_tir**

The equation for ΔF_{net} is now given before defining ΔF_{sol} and ΔF_{tir}. Please section see section 2.1 in the manuscript or the diff file.

5. **Line 95: "The surface albedo is kept constant in this study". Which value is chosen for the solar spectrum?**

   The surface albedo in the solar is set to values between 0 and 1, which are specified and discussed later in the paper. Therefore, the sentence has been moved to subsection "2.2 Radiative transfer simulation set-up". That section now reads:

   > *"The Earth's surface albedo, α_{srf} ranges from 0 to 1, which represents the full possible range. In general, α_{srf} varies spectrally but here is kept constant for all solar wavelength. It is varied between 0 and 1 to include surface conditions ranging from open ocean to full sea ice or snow (Baldridge et al., 2009; Gardner and Sharp, 2010; Meerdink et al., 2019; Gueymard et al., 2019). Values of αsrf are given in Table 4. In the TIR wavelength range α_{srf} is assumed to be 0, which leads to an emissivity $\varepsilon = 1$ with the Earth's surface thus acting as a blackbody (Wilber, 1999)."*

6. **Line 102: "libRadtran was run as one-dimensional (1D) RT solver…" -> better: "The 1D RT solver DISORT, which is part of libRadtran, assuming horizontally uniform clouds".**

   We thank the Reviewer for this suggestion and we modified the sentence accordingly.

   > *"The radiative transfer solver DISORT (Buras et al., 2011) allows to select 2N -number of streams to be used in the radiative transfer simulations. [...]"*

7. **Line 119: Why would tropical and desert atmospheric profiles be interchangeable here? The different water vapor profiles affect the thermal RE as mentioned in the subsequent sentence.**

   Tropical and desert atmospheric profile are not interchangeably. The amount of water vapor, especially in the lower atmosphere h< 6 km differs. Here we refereed to the surface temperature only and not to the vertical profile. Nevertheless, we follow the suggestion of the Reviewer and remove 'desert' from the sentence. This is in line with the adjusted surface temperature as the upper bound of surface temperature was changed from 16°C to 27°C (due Reviewer comment directly below). A surface temperature of 27°C are representative for tropical regions but not necessary for desert regions, which can have much higher surface temperatures. 27°C are selected as a compromise to match the lowermost temperature of the atmosphere profile (please see the comment below). In addition, we added a sensitivity study to estimate the effect of variations in the relative humidity profile. A dedicates section can be found in section 3.5. Please see the adjusted sections in the diff file.

8. **Line 121: Please double-check the surface temperatures for the subarctic winter and tropical profiles. Surface temperatures for subarctic winter is 257.2 K and 299.7 K for tropical. How is the surface temperature "set" to -40, 0, 40 degC?**

The Reviewer is right. The previously selected temperature in the atmosphere profile and the surface temperature caused a discontinuity. In the new simulations, the surface temperatures are set to the temperature of the lower most value of the selected atmosphere profile.

9. **Line 143: "Our simulations range from 5 to 45 µm for all three shapes and, therefore, focus on young contrails and cirrus." If so, aged contrails and contrail cirrus should not be mentioned in the abstract and conclusion.**

   The Reviewer is right. With the new setup and repeated simulations ice particle size ranges from 5 to 85 µm, which also includes more mature contrails and cirrus clouds. (Krämer, A microphysics guide to cirrus – Part 2: Climatologies of clouds and humidity from observations, 2020, Atmos. Chem. Phys. , 20, 12569-12608, 2020).

10. **Table 3: Range does not add information here, just provide actual values. Add "total number" as last column label.**

    The column 'range' has been removed and the last column is labeled 'total number of simulations'. Please see the diff file for the modifications.

11. **Line 185: "because, as 3D effects are neglected" -> "as radiative 3D effects are neglected". This is the first time 3D effects are mentioned, but this information should appear more prominently. Please cite relevant literature and add more discussion on possible biases introduced by the plane-parallel assumption and neglecting 3D RT in this study.**

    Following this comment and comments from the other Reviewers, we provide a paragraph in sections "1. introduction" and "2.2 Radiative transfer simulation set-up". Please also see the response to the general comment number 2 of Reviewer 3.

12. **Results Fig. 1: it should be noted that these results do not rely on RT simulations but show basic dependencies between microphysical and optical parameters.**

    The ice crystal number concentration (Fig1a) was calculated with equation 13, assuming spherical ice crystals (approximation for droxtals) and assuming a mono-disperse particle size distribution. The cloud optical thickness used in Fig. 1 b,c,d is obtained from libRadtran simulations (verbose file) using ice optical properties of droxtals. It is now detailed how Fig. 1 is created in the text and the caption.

    > *"We first provide an overview of how r_{eff} and IWC determine the cloud optical and microphysical properties. Figure 1a–d illustrates the dependence of N_{ice} and τ_{ice} as a function of r_{eff} and IWC. Nice is approximated by Eq. 14, assuming droxtals (almost spherical ice crystals), a mono-disperse particle size distribution, and a cloud geometric thickness dz of 1000 m. The ice cloud optical thickness τ_{ice} at 550 nm wavelength, given in Fig. 1b–d, is directly calculated by libRadtran using optical properties from droxtals."*

13. **Line 225: “Going beyond these dependencies…” The sensitivities discussed in the preceding paragraph do not use RT simulations. Now switch to RT results? This should be separated more clearly in the text.**

The sentence in this section was rephrased to be more clear in this aspect. Please also see the previous comment.

14. **Fig. 1c, d: please complete legend information with “r_eff” (1c) and “IWC” (1d)**

A title was added to both legends.

15. **Line 245: why are the parameters for the reference cloud chosen from extreme values of the parameter space? Wouldn’t it be more intuitive to select mean/median values?**

Similar to Meerkötter et al. (1999), we selected the extreme values to mark either end of the simulated parameter range. Using mean values would not allow to explicitly mark the upper or lower boundary, and to investigated the effect of spanning the full range of a given parameter.

16. **Please provide a reference from literature which states a representative cirrus optical thickness of 0.18 at 640 nm?**

Iwabuchi (2012) used CALIPSO Lidar observations and determined a mean COT of contrails of 0.19 (532nm). Nevertheless, thicker contrails may exist. The reference was added to the section. (Iwabuchi, H. / Yang, P. Liou, K. N. / Minnis, P.; Physical and optical properties of persistent contrails: Climatology and interpretation, 2012, J. Geophys. Res. Atmos. , Vol. 117, No. D6)

> *“[…] this leads to a* τ_{ice} *of 0.46 at 550 nm wavelength, which is representative for contrails and young cirrus (Iwabuchi et al., 2012). [...]”*

17. **Which crystal shape is assumed for the reference cloud?**

This information was added.

> *“The reference cloud is assumed to consist of rough-aggregates.”*

18. **In Fig. 2 it looks like reff=5 um is used for the reference cloud, not 45 um.**

This was adjusted. Now a cloud with 85 µm is used.

19. **Figure 2:**

- **The scale and grid lines of the y-axis should be comparable between the 3 subplots.**

Grid lines have different spacing to maintain clarity in the SW plot and to provide sufficient guidelines in the TIR and net plot. For better comparability we changed gridlines to an equal spacing.
However, we keep the different *y* axis otherwise the bars in the net become too small for differences among the parameters to be legible.

- **Caption: The parameter for the reference case provided here do not match the description in the text.**

  The caption and the text have been homogenized.

- **Selecting mean/median values of the parameter space would place the star closer to the mean RE, similar to the IWC case.**

  We selected either end of the parameter space to clearly show how ΔF varies, when the one of the parameters is varies to the other end of the parameter space.

- **Is a box plot representative for the 3 distinct ice crystal shape values?**

  Following this question, we separated the data of the three shapes and present them individually. In that way the discrete differences from the shape effect become clearer.

20. **Line 249: “For the all Sun geometries…” Please double-check sentence.**

  “The” has been removed from the sentence.

  > *“For all Sun geometries[…] “*

21. **Line 274: Which values for the surface albedo were selected to investigate the sensitivity of the RE on T_srf, T_ic and tau_wc? The results should be different for alpha=0, and 1.**

  In the introduction of the reference cloud, a surface albedo value of 1 was given. To be clearer, we added a sentence at the beginning of this paragraph that explicitly states the surface albedo

  > *“The influence of a varying surface temperature T_{srf} or cirrus temperature $T_{cld,ice}$ (related to cloud base altitude), are investigated for a cloud scenario with a solar surface albedo $\alpha_{srf,sol}$ set to 0. [...]”*

22. **3.1 Sensitivity on ice crystal shape: When comparing the effect of ice crystal effective radius vs. crystal shape on the cirrus RE, it is important to mention that size and aspect ratio are coupled in the optical property parameterizations by Yang et al. 2000 and 2013. Please add this to the discussion.**

  Section 3.1 was extended an it is now mentioned that the maximum dimension of an ice crystal and the aspect ratio are coupled.

  > *“[…] Furthermore, the ice optical properties by Yang et al. (2010, 2013), which are used for the RT simulations in the present paper, based on a coupling of the maximum diameter of the ice crystal and the aspect ratio, with the later one being different for each particle shape [...]”*

23. **Figure C1: why not show the phase function for the ice crystal shapes and effective radii which are actually used?**

We follow the advice of the Reviewer and plot the phase functions for r_{eff} of 5, 25,55, and 85 µm, which are the newly selected values for the simulations. Please see the revised diff file.

Literature:

- **Kalesse, H., 2009. *Influence of ice crystal habit and cirrus spatial inhomogeneities on the retrieval of cirrus optical thickness and effective radius* (Doctoral dissertation, Mainz, Univ., Diss., 2010).**
- **Gounou, A. and Hogan, R.J., 2007. A sensitivity study of the effect of horizontal photon transport on the radiative forcing of contrails. *Journal of the atmospheric sciences*, *64*(5), pp.1706-1716.**
- **Forster, L., Emde, C., Unterstrasser, S., and Mayer, B. 2012. Effects of three-dimensional photon transport on the radiative forcing of realistic contrails. *Journal of the atmospheric sciences*, *69*(7), pp.2243-2255.**
- **Platnick, S., Meyer, K.G., King, M.D., Wind, G., Amarasinghe, N., Marchant, B., Arnold, G.T., Zhang, Z., Hubanks, P.A., Holz, R.E. and Yang, P., 2016. The MODIS cloud optical and microphysical products: Collection 6 updates and examples from Terra and Aqua. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(1), pp.502-525.**
- **Forster, L. and Mayer, B., 2022. Ice crystal characterization in cirrus clouds III: retrieval of ice crystal shape and roughness from observations of halo displays. *Atmospheric Chemistry and Physics*, *22*(23), pp.15179-15205.**
- **Järvinen, E., Jourdan, O., Neubauer, D., Yao, B., Liu, C., Andreae, M.O., Lohmann, U., Wendisch, M., McFarquhar, G.M., Leisner, T. and Schnaiter, M., 2018. Additional global climate cooling by clouds due to ice crystal complexity. *Atmospheric Chemistry and Physics*, *18*(21), pp.15767-15781.**