Reply to Reviewer #1
(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-RC1, 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*.

General Comments:

The overall concept of this study is commendable and very useful, but there are problems with this study that need to be addressed and resolved before this study can be published. In spite of these problems, the results still appear valid. For example, the authors attempt to treat cirrus cloud properties (effective radius reff or diameter D_{eff}, IWC and N_{ice}) using Euclidean geometry (i.e., as spheres), and as with earlier attempts like this, at least one of these variables ends up serving as the "dust bin" (i.e., becomes corrupted, Nice in this case) due to this flawed approach. But since it appears that D_{eff} and IWC are calculated accurately, and the radiation transfer (RT) calculations in libRadtran do not use N_{ice}, the results of this study still appear valid.

Another major drawback of this study is that the cirrus cloud geometrical thickness Δz is fixed (i.e., it never varies), having a value of 0.20 km. It appears that Δz is fixed to enable mathematical closure; otherwise Figure 1 is not possible. More importantly, Δz = 0.2 km is fine for contrails, but not for natural cirrus clouds, which are typically ~ 1.2 km on average. Since this study claims to be representative of natural cirrus clouds, the authors need a compelling argument to justify using a fixed Δz of 0.2 km for such clouds.

The paper is well written and organized, with good quality of figures, and the results should be useful to the atmospheric radiation community. I therefore recommend publication after major revisions. Detailed comments addressing the paper's drawbacks now follow.

We address these comments below.

Major Comments:
1. Equation 1: In some conventions, F↓ is taken to be positive while F↑ is taken to be

negative, in which case $\Delta F = F_c + F_{cf}$. To avoid any confusion, please mention that all flux quantities are taken to be positive.

The manuscript explains that all values are taken positive. We rephrased the sentence and made it clearer:

> *"where the upward and downward, cloudy and cloud-free irradiances are all counted positive."*

2. Lines 127-128: Cirrus clouds are typically ~ 1 km in geometrical thickness; why was a thickness of 0.2 km selected? It is not clear how this unrealistic value impacts the analysis under "Results"; please explain why the findings of this study are realistic in relation to this choice for geometrical thickness.

The Reviewer is right. While 0.2 km is realistic for contrails, the value is untypical for natural cirrus. Considering also the comments be the other Reviewers, the simulations have been revised. In the new simulations the cloud geometric thickness is set to 1 km to represent aged contrails and natural cirrus. Selecting a cloud geometric thickness of 1 km is supported by citing the relevant literature.

> *" […] Within the simulations, the ice cloud geometric thickness dz is set to 1000 m for all simulations, which represents an average for observed contrails as well as natural cirrus (Freudenthaler 1995, Sassen 2001, Noel 2007, Iwabuchi 2012."*

3. Equation 6: Petty and Huang (2011) was consulted for the calculation of ν_{eff}, where it was discovered that ν_{eff} has no general analytical solution, making Eq. 6 here unpractical. If there is an analytical solution, it should be given here. For the special case of an exponential particle size distribution or PSD, $\mu = 0$ and $\nu_{eff} = 1/3$, but libRadtran has set μ to a value of 1.

The Reviewer is right. The analytical solution is only available for $\mu = 0$ with $\nu_{eff} = 1/3$ and $\Lambda=3/r_{eff}$. In libradtran, μ is set to 1 and ν_{eff} is set to 0.25, which is based on observations of ice particle size distributions (Evans 1998; Heymsfield 2002). The entire section and set of equations were revised and we direct the Reviewer to the provided diff-file for the new text.

4. Lines 155-157 and Eq. 7: Please mention that this Deff definition is the same definition derived in Mitchell (2002, JAS), provided that ice volume V is evaluated at the bulk density of ice (0.917 g/cm3), as shown by the following derivation that begins with Eq. 7: Deff = DV3/DA2 = (6V/π)/(4A/π) = (3/2) (V/A) (1) where V is the ice crystal volume at bulk density and A is the mean projected area of the ice crystal, as defined on lines 159-160. But on line 164, the paper states: "where V and A are the average volume and projected area of the crystal population, respectively". It seems like a leap of faith to apply this Deff derived for an ice crystal to a PSD, but in Mitchell (2002) it is shown that this can be done, so please justify this leap of faith and mention the implicit ice density.

This comment is linked with comment 3 above. The entire paragraph was modified, the citation to Mitchel (2002) is included, and we direct the Reviewer to the diff file for the new text.

5. Equation 11: This could be done more elegantly and accurately by simply selecting appropriate power-law mass-dimension expressions for aggregates, droxtals, hex-plates. From Eq. 29 in Mitchell et al. (2006), $N_{ice} = \Gamma(\mu+1)\ IWC\ \Lambda^{\beta} / (\alpha\ \Gamma(\beta+\mu+1))$, (2) where Γ denotes the gamma function, μ and Λ are from Eq. 5 of this paper, and α and β are the prefactor and exponent of the ice particle mass-dimension power law relationship (i.e., $m = \alpha D^{\beta}$). The r^3 dependence in Eq. 11 is an artifact of the Euclidean geometrical framework imposed and leads to false interpretations later in the paper, like the top of page 12. For example, from Petty and Huang (2011), $\Lambda = 3/r_e$ for exponential PSDs, giving $N_{ice} = 3^{\beta}\ IWC/(\alpha\ \Gamma(\beta+1)\ r_e^{\beta})$. (3) Thus, N_{ice} has a β dependence on ice particle size (not a cubic dependence as shown in Eq. 11), where β tends to be ~ 2 for aggregates, ~ 2.4 for hex-plates and 3 for droxtals.

The equation was intended to provide a rough guidance for the reader. Nevertheless, the Reviewer is right and the suggested relationship more accurately represents nature. The set of equations and the accompanied text have been revised. Please see the diff file.

6. Lines 199-200: The cloud absorption optical depth is also very important in determining RT in the TIR; please mention this.

The Reviewer is right. However, in course of the revision of the paper the section about blackbody emission has been removed from the paper.

7. Equation 13: Is this equation used in libRadtran? If not, what is the point in mentioning it? Cloud property input to libRadtran consists of IWC and re, suggesting the zero-scattering approximation might be used for TIR hemispheric fluxes: $\varepsilon = 1 - \exp(-5\ \tau_{abs}/3)$ (4) where ε is cloud emissivity and τ_{abs} is the cloud absorption optical depth. Please indicate whether ε is calculated in libRadtran, and how it is calculated if applicable.

The DISORT solver in libradtran (Buras et al 2011) calculates scattering in the TIR on basis of the bulk-scattering properties of ice crystals, analog to the solar wavelength range. Thus, the zero-scattering approximation is not used in the simulations. Equation 13 was added to the manuscript to provide guidance for the reader. To avoid misinterpretation the equation is brought into context and is expanded to section “2.4 Approximation of radiative transfer in the thermal-infrared”, to incorporate suggestions from other Reviewers.

8. Lines 209 – 213 and Eq. 14: Eqn. (14) appears flawed since, in principle, there should be an emissivity term (ε) for both the surface and the ice cloud. But since typically ε ≈ 1 at the surface, does ε in (14) correspond only to the ice cloud? If so, it would be incorrect to multiply it by T_{sfc}^4 (which Eq. 14 does). Later, ΔF_{tir} is shown for IWC, re, and ice crystal shape, so it appears that ε refers to the ice cloud and therefore ε < 1, but how then does ε depend on IWC, re and ice particle shape? The dependence of ΔF_{tir} on cloud properties is a complete black-box mystery and this needs to be explained.

As mentioned in our reply to comment 7, a dedicated section for TIR RT was added to the manuscript. It is primarily based on the TIR RT approximation given by Corti and Peter (2009). Equation 14 is now replaced by Eq. 20. Major steps to derive Eq. 20 are given in the manuscript; details can be found in Corti and Peter (2009).

9. Figure 1: Fixing the cloud thickness appears to be required to get closure for the system of equations producing these four figures. If so, this analysis may not be representative of natural cirrus clouds in some respects since the geometric cloud thickness Δz is fixed at 0.2 km corresponding to extremely thin cirrus or contrails. For example, obtaining a typical range of cirrus cloud optical depth requires anomalously high IWC to compensate for the small Δz, based on the relationship: τ_{vis} = 3 IWC Δz/(ρi Deff). At a minimum, the authors should explain how they obtain mathematical closure to produce these plots.

All simulations have been repeated with a cloud geometric thickness of 1 km. Figure 1 has been revised accordingly. The method to calculate the concentration of ice crystals is given.

> *"[…] N_ice is approximated by Eq. 14, assuming droxtals (almost spherical ice crystals), a mono-disperse particle size distribution, and a cloud geometric thickness dz of 1 km. [...]"*

10. Figure 9a: Nice here has units of cm-3 with some values exceeding 100 cm-3. In natural cirrus clouds, Nice_ice rarely exceeds ~ 2 cm-3. This appears to be a consequence of the r-3 dependence of Nice in Eq. 11. As shown in Eq. 3 above, the dependence of N_{ice} on re is re-β where β typically lies between 1.7 and 3.

In line with the previous comments a sentence is given that explains the calculation. N_{ice} is approximated by Eq. 15, assuming droxtals (almost spherical ice crystals), a mono-disperse particle size distribution, and a cloud geometric thickness d*z* of 1 km. The cloud optical thickness τ_{ice} at 550 nm wavelength is directly calculated by libRadtran using optical properties from droxtals. Please see the previous comment(s) and annotations as well as the diff file.

11. Lines 258-259: As noted in (1) above, Nice is related to reff by the power of -β (not -3 as stated here).

The Reviewer is right and the sentence has been modified accordingly.

> *"As expected, variations in r_{eff} have the largest effect on the solar, TIR, and net ΔF , as Nice relates to r_{eff} by the power of −β, which depends on the particle shape (see Sec. 2.3 and Eq. 14). [...]"*

12. Lines 295-296: How do ice particle shapes affect ΔFtir, given the above comments in 8?

As stated in comment 8, RT simulations with DISORT rely on the single-scattering albedo, which depends on the particle size distribution, ice water content, and selected effective radius. Keeping IWC and the effective radius constant but changing the particle shape directly influences the particle size distribution and the related effective radius. The Reviewer points out that Mitchell (2002, JAS) and Mitchell et al. (2011, ACP) found that the shape of the PSD matters considerably for LW radiation and the ice water content and effective radius is not sufficient to describe the radiative properties of ice clouds. We added this information to the manuscript.

> *"The spread in ΔF_{sol} across crystal shapes with the same r_{eff} and IWC can be interpreted as a potential uncertainty in ΔF_{sol} due to the ice crystal shape. One has to keep in mind that the differences partially result from deviating crystal size distributions as these depend on the selected crystal shape. Macke et al. (1998) showed that, in the solar wavelength range, the crystal shape is the main driver and the actual ice particle size distribution has only a minor effect on ΔF_{sol}. Nevertheless, Mitchell et al. (1996) and Mitchell et al. (2011) found that the particle size distribution also has a considerable impact on ΔF_{tir}, leading to differences of up to 48% in the single-scattering albedo, when switching between PSD. [...]"*

13. Lines 307-314: The aspect ratio strongly impacts the scattering phase function and therefore the asymmetry parameter g (Fu, 2007, JAS; Van Diedenhoven et al., 2012, AMT; 2013, ACP). Please consult these studies and revise this discussion accordingly.

The Reviewer highlights an important fact. The aspect ratio has a significant influence on the asymmetry parameter and we added this information to the manuscript. The entire section was revised. Please see the diff file for the revised version.

> *"Scattering and absorption by an ice crystal is characterized by its orientation, complex refractive index of ice, the wavelength of the incident light, shape, size, and the resulting asymmetry parameter. The asymmetry parameter is a measure of the asymmetry of the phase function P between forward and backward scattering (Macke et al., 1998; Fu, 2007). P provides the angular distribution of the scattered direction in relation to the incident light. For example, in case of idealized hexagonal ice crystals and wavelength below 1.4 µm, the asymmetry parameter is primarily determined by the ice crystal shape / aspect ratio but for wavelength larger then 1.4 µm the asymmetry parameter also depends on the ice crystal size (Fu, 2007; Yang and Fu, 2009; van Diedenhoven et al., 2012). Consequently, the assumption of an ice crystal habit and ice crystal size, with related aspect ratio, are vital information to estimate the ice cloud RE."*

14. Figure 3 caption: What do the numbers refer to in Fig. 3 a-c?

A sentence was added to explain the meaning of the numbers.

> *"The numbers indicate the optical thickness simulated for the reference cloud that contains ice aggregates."*

15. Lines 327-329: Macke and Grosklaus (1998) addressed lidar (SW radiation). While their finding about PSDs may be true for SW radiation, Mitchell (2002, JAS) and Mitchell et al. (2011, ACP) found that PSD shape matters considerably for LW radiation.

The Reviewer highlights an important point, which is now mentioned in the manuscript. The respective text is included in the modified section quoted in the reply to comment 12.

16. Line 358: This refers to Fig. 5a, correct? Here the upper boundaries are becoming more negative with increasing θ.

This is correct. The paragraph is introduced explicitly referring to Figure 5a.

17. Figure 5 caption: What do the numbers next to the boxes indicate? They appear to correspond to median, 25th and 75th percentile values, but this should be called out.

We added a sentence that explains the figures.

> *“[…] Red and black numbers indicate the 25th- and 75th percentiles, as well as the median value, respectively.”*

18. Line 378: As far as I can tell, Fig. 2 shows that reff is the primary factor controlling ΔF, not IWC.

The Reviewer is right. The sentence has been changed.

> *“As presented in Fig. 2, the IWC is the second most influencing factor that controls ΔF. […]”*

19. Lines 506-508: This could have been described more clearly under “Methods” unless I missed something.

We agree with the Reviewer and added a paragraph that describes the sampling method more clearly. It is added to section “3 Results” to help to understand the results.

> *“To go beyond these basic dependencies, the impact of each parameter is estimated by fixing one parameter at a time, while the others can vary. For example, in case of r_{eff} , all simulations, for steps of r_{eff} given in Table 4, are extracted from the 8-D hypercube. The extracted sub-sample, in the example for a specific r_{eff} , is used to calculate the distributions of solar, TIR, and net ΔF . These distributions are then visualized by box plots and characterized by their minimum, maximum, median, as well as the 25th- and 75th-percentiles. This strategy can be interpreted as a type of sub-sampling, by averaging all unfixed parameters to project ΔF onto the one-dimensional space [...]”*

Technical Comments:

1. Figure 2 caption: Typo where reff = 5 μm; should be 45 μm?

The Reviewer is right and the typo has been fixed and adapted the new upper boundary of 85 μm.

2. Line 349: ΔFtir => ΔFnet?

The Reviewer is right and the sentence has been changed accordingly.