Comment to Wolf et al., “Radiative effect by cirrus cloud and contrails – A comprehensive sensitivity study”, in review

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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:

Input LW RE approx. of Schumann et al. (2012)	**Data from Wolf et al. (2023)**
Outgoing longwave radiation	Upward thermal infrared irradiance (`Fup_tir`)
Atmospheric temperature at contrail midlayer	Ice cloud temperature (`ice_cloud_temp`)
Contrail optical thickness at 550 nm	Ice cloud optical thickness at 640 nm (`tau`)
Optical thickness of cirrus above contrails	Set to zero
Contrail ice particle volume mean radius r_vol	Derived from ice crystal effective radius (crystal_effective_radius) using Aggregates: r_eff = 0.574 r_vol Droxtals: r_eff = 0.94 r_vol (Schumann et al., 2011)

The shortwave cloud radiative forcing needs 6 different inputs:

Input LW RE approx. of Schumann et al. (2012)	**Data from Wolf et al. (2023)**
Solar direct radiation	Downward solar irradiance (`Fdn_sol`)
Reflected solar radiation	Upward solar irradiance (`Fup_sol`)
Solar constant	1361 W/m²
Contrail optical thickness at 550 nm	Ice cloud optical thickness 640 nm (`tau`)
Optical thickness of cirrus above contrails	Set to zero
Contrail ice particle volume mean radius r_vol	Derived from ice crystal effective radius (crystal_effective_radius) using Aggregates: r_eff = 0.574 r_vol Droxtals: r_eff = 0.94 r_vol (Schumann et al., 2011)

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.

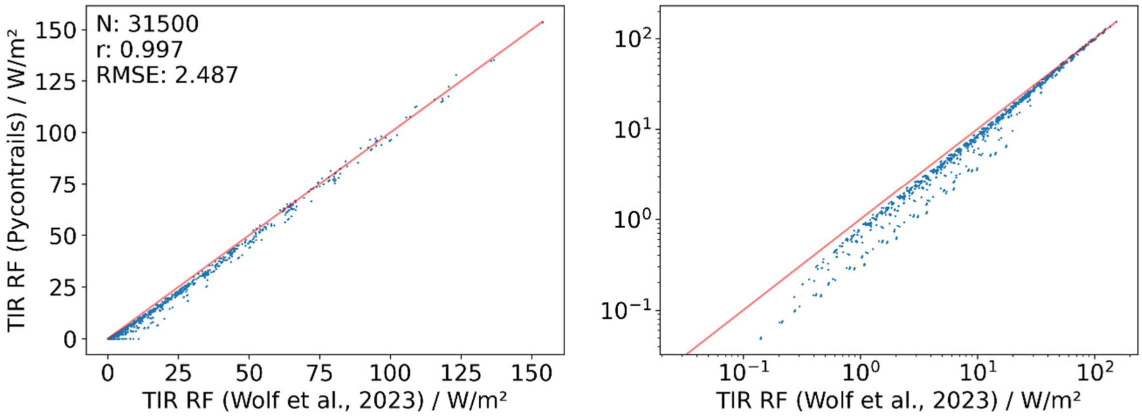
Note that the cirrus optical depths provided by Wolf et al. and used in the approximation of Schumann et al. (2012a) are for different wavelengths (640 and 550 nm, respectively). However, we assume that the differences in the ice optical properties are in the order of few percent (Lynch & Mazuk, 2001)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

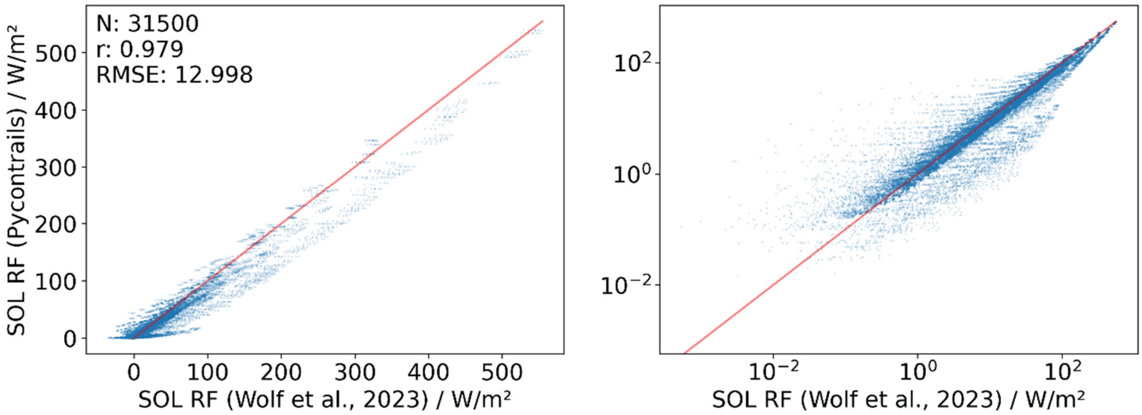
Nevertheless, we find that the results of Wolf et al. and the approximations of Schumann et al. (2012a) are in reasonable agreement (see plots below), with Pearson correlation coefficients of 0.979 and higher. The longwave radiative forcing based on Schumann et al. (2012a) is slightly smaller than the 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).

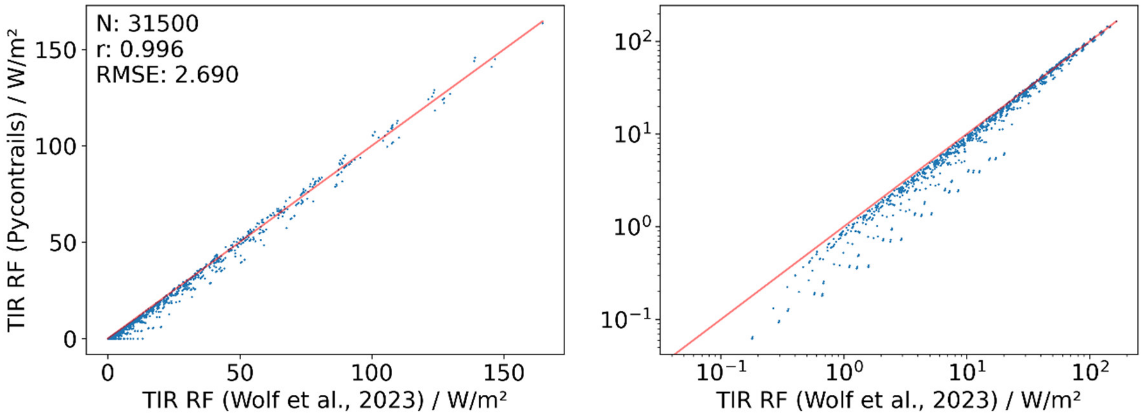
Aggregates



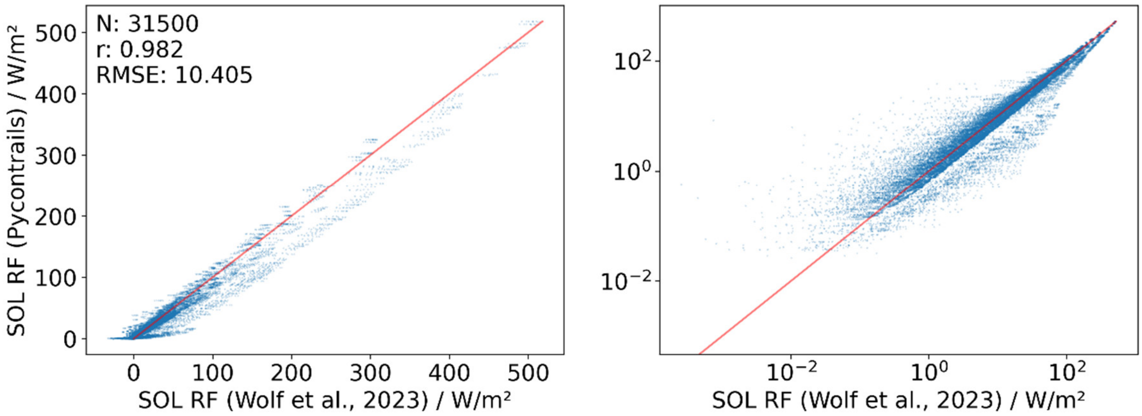
Aggregates



Droxtals



Droxtals



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?
    b) any other absorbing gases or species (O3, CO2, aerosols)?
- 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.
- 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.
- 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?
- Why do you use the older Fortran version of libRadtran? The more stable C-Version is available since 2010.
- 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.
- 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 ρ_{ice}. More important (besides ρ_{ice} 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?

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?
- 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).
- 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).

- 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).
- 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).
- 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.
- 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 β_{ext} for given IWC and temperature (Heymsfield et al., 2014), but $\tau \sim \beta_{ext}$ D, by definition, is the parameter which characterizes the impact of a cloud layer on radiation transfer.
- 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.

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.

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