

**Impacts of ice-nucleating particles on cirrus clouds and radiation derived from global model simulations with MADE3 in EMAC**  
**C. Beer, J. Hendricks and M. Righi**  
**Replies to referee comments – 2<sup>nd</sup> phase**

We are grateful and thank the reviewers for their valuable comments in this second round of reviews. Please find our point-by-point reply below (reviewers' comments are marked in blue, authors' reply in black, and text quotes in *"italic red"*).

**Reply to Reviewer #1**

**Minor comments:**

Lines 452-454: I think this sentence could be woven into the introduction (below line 79) in order to better motivate your study. A one sentence summary and conclusion based on this result could be added behind line 519. If I understand it right, your study finds a much smaller effect using more realistic assumptions.

Thank you for the suggestion. We added this aspect to the introduction as suggested:

*Line 79: "By designing the simulation experiments for this analysis according to the study by Gasparini and Lohmann (2016), we improve the comparability and aim to explore the robustness of the resulting quantifications of the INP-cirrus effects presented here by comparing with a similar model study."*

Lines 38-41 and elsewhere: I think it would be better to default to the term ERF instead of RF. Although it is good to mention that nudging may suppress some of the responses to changing INP, I suggest to nevertheless use the term ERF. Because of the absence of water vapor nudging, the nudging here suppresses only responses via dynamics, which I think can have only a very small effect. Therefore, as far as I can see, you are actually computing ERF. (The lack of statistical significance in the free running model is almost certainly due to larger variability between the runs and therefore does not reflect differences in the magnitude of the ERF.)

We agree and use the term ERF instead of RF in the text, while still commenting on possible nudging impacts.

*(line 208) "The radiative forcings reported here explicitly consider the impact of cloud adjustments, as we are employing an aerosol-cloud coupled model. The RF values presented in the following can therefore be regarded as approximations of effective radiative forcings (ERF), although the use of model nudging may tend to suppress some feedbacks (see Sect. 4.3). Therefore, we use the term ERF in the following."*

**Technical:**

Line 184: as presented -> has been presented

We rephrased this sentence to make easier to read:

*"In Fig. S1, we present a comparison of aerosol number concentrations for the different model resolutions, which complements Fig. 5 of Beer et al. (2020) with the results for the T42L41 resolution applied in the present study."*

**Reply to Reviewer #2**

**Specific comments**

- Beer et al, findings refer to a possible larger INP effect due to lower model spatial resolution but they have not quantified the impact of the spatial resolution to the radiative forcing (RF), which is one of the of key aspect of the paper. Would it be possible? How much the RF changes (in %) compared to the higher resolution? This additional information will enable a more comprehensive and accurate assessment of your RF estimations, allowing for a better interpretation of the results.

We agree that the impact of an increased horizontal model resolution on the simulated INP-cirrus effects is an important aspect. However, the model simulations presented here rely on the extensive tuning of cloud and radiation properties performed by Righi et al. (2021). Going to a different model resolution would require a complete retuning of the model, which would in turn require performing a large number of (quite expensive) tuning simulations. This is not possible for the present study. However, we aim to analyze this aspect in the future and already mentioned this in the text:

*(line 199) “Nonetheless, the applied model resolution can influence the simulated INP-cirrus effects and this impact should be the focus of future studies.”*

- L. 185 “a factor 2 to 3 larger”, which translates to how much RF difference? Could you quantify the term “larger’ in terms of RF?

At present we cannot quantify the impact of increasing model resolution on the RF. We aim to analyze this in a subsequent study (see our reply to the comment above).

- I recommend incorporating the spatial resolution sensitivity results into the conclusions section, highlighting the advantages and disadvantages of using this spatial resolution.

Thank you. We follow the suggestion and mention the sensitivity to the model resolution in the conclusion section. We also include some remarks on the use of model nudging in this paragraph.

*(line 508) “We analyze and discuss the uncertainties regarding the INP-cirrus effects presented here. The use of model nudging can influence the simulated INP-effects due to suppressing feedback mechanisms that would occur in the free-running mode. However, simulation results using the nudging technique are similar to those performed in the free-running mode. Additionally, the use of model nudging is important to achieve statistically significant results. We discuss possible model dependencies on the applied model resolution, which can influence the simulated INP concentrations, as well as cloud formation processes. For example, an increased horizontal grid resolution can lead to reduced INP number concentrations (about a factor of 2 in the cirrus regime). Therefore, the impact of the applied model resolution on the resulting climate forcing due to INPs should be the focus of future studies.”*

- I would suggest to merge L. 400- 410 (“The resulting global RF...”) in section 4.3 on model nudging to Sec 4.4. On the other hand, which is the added value of 391-400 lines?

These lines particularly focus on the impact of model nudging, which could potentially impact the INP-cirrus effects due to suppressing some feedbacks. Section 4.4 discusses further uncertainties that are not analyzed in detail in this study (e.g. by performing sensitivity experiments). Therefore, we think this fits better in Sect. 4.3, as this subsection is specifically dedicated to the impact of model nudging.

- Figure 5 shows the impact of AmSu compared to the “heterogeneous freezing case on DU and BC”, did you calculate the AmSu RF with the homogeneous freezing case only?

We chose the case with DU and BC INPs as a reference here, in order to analyze the impact of adding the newly implemented AmSu INPs to the population of DU and BC, which are usually considered as INPs in the cirrus regime by global models. In the same way we analyzed the impact of adding glassy organic INPs to the population of DU and BC. Therefore, we did not quantify the impact of only AmSu compared to purely homogeneous freezing. However, we appreciate this suggestion and may consider it for future analyses.

- L. 297-298 Fig. 5 and Fig. 4 refer to different reference cases and the results are not directly comparable.

We agree that these two results are not directly comparable due to the different baseline cases. For this reason, we chose to show these effects in two different figures. We explicitly mentioned the different baseline in the figure caption and in the text.

*(line 293) “This is calculated as the difference between a simulation including AmSu, DU and BC INPs, and a simulation including only heterogeneous freezing on DU and BC.”*

*(Fig. 5 caption) "... calculated from the difference between a simulation including AmSu, DU and BC INPs, and a simulation including only heterogeneous freezing on DU and BC. [...] Note the different reference case with respect to Fig. 4."*

- Please correct "As in Fig." recurrent in most of the figures. Consider moving some Figures in the supplementary to lighten the text if necessary, instead of reducing the caption's text. A Figure has to be self-consistent in the caption. You do not discuss all the parameters in the Figures, so please also consider to move some panels to the Supplementary material instead of shortening the caption.

Thank you for the suggestion. We included some additional information in the figure captions.

*(Fig. 3 caption) "... spatially averaged above the 400 hPa level and considering multi-year averages over the simulated period (2001–2010)."*

*(Fig. 4 caption) "... Global and latitude-specific, regional differences are shown for (a) total all-sky, (b) all-sky shortwave, (c) all-sky longwave, (d) clear-sky shortwave, (e) clear-sky longwave top-of-the-atmosphere ERFs. Panels (f-i) depict relative changes in the all-sky ICNC, fraction of homogeneously formed ice crystals, total water (as the sum of water vapour and ice water), and cloud occurrence frequency, all spatially averaged above the 400 hPa level, considering multi-year averages over the simulated period (2001–2010)."*

*(Fig. 5 caption) "... Global and latitude-specific, regional differences are shown for (a) total all-sky, (b) all-sky shortwave, (c) all-sky longwave, (d) clear-sky shortwave, (e) clear-sky longwave top-of-the-atmosphere ERFs. Panels (f-i) depict relative changes in the all-sky ICNC, fraction of homogeneously formed ice crystals, total water (as the sum of water vapour and ice water), and cloud occurrence frequency, all spatially averaged above the 400 hPa level, considering multi-year averages over the simulated period (2001–2010)."*

*(Fig. 6 caption) "Multi-year global averages (years 2001–2010) of changes in (a) total all-sky, (b) all-sky shortwave, (c) all-sky longwave, (d) clear-sky shortwave, (e) clear-sky longwave top-of-the-atmosphere ERFs, and relative changes averaged above the 400 hPa level for (f) all-sky ICNC, (g) the fraction of homogeneously formed ice crystals, (h) total water (as the sum of water vapour and ice water), and (i) cloud occurrence frequency due to the total INP-cirrus effect, considering the difference with respect to the purely homogeneous freezing case, for different values of the vertical velocity, all spatially averaged above the 400 hPa level and over cloudy and cloud-free grid boxes. Confidence levels (in %) are shown for each bar. Significant and non-significant results are represented by filled and hatched bars, respectively."*

*(Fig. 8 caption) "As in Fig. 7, but showing zonal averages of changes in (a) total all-sky, (b) all-sky shortwave, (c) all-sky longwave, (d) clear-sky shortwave, (e) clear-sky longwave top-of-the-atmosphere ERFs, and relative changes averaged above the 400 hPa level for (f) all-sky ICNC, (g) the fraction of homogeneously formed ice crystals, (h) total water (as the sum of water vapour and ice water), and (i) cloud occurrence frequency, considering multi-year averages over the simulated period (2001–2010). Non-significant values are shaded in grey."*

*(Fig. 9 caption) "As in Fig. 7, but showing multi-year averages (years 2001–2010) of the effect of highly efficient INPs (assuming  $S_c = 1.05$ ,  $f_{act} = 1.0$ ) for different prescribed concentrations, considering changes in (a) total all-sky, (b) all-sky shortwave, (c) all-sky longwave, (d) clear-sky shortwave, (e) clear-sky longwave top-of-the-atmosphere ERF, and relative changes averaged above the 400 hPa level for (f) all-sky ICNC, (g) the fraction of homogeneously formed ice crystals, (h) total water (as the sum of water vapour and ice water), and (i) cloud occurrence frequency."*

*(Fig. 10 caption) "As in Fig. 9, but showing zonal averages of changes in (a) total all-sky, (b) all-sky shortwave, (c) all-sky longwave, (d) clear-sky shortwave, (e) clear-sky longwave top-of-the-atmosphere ERFs, and relative changes averaged above the 400 hPa level for (f) all-sky ICNC, (g) the fraction of homogeneously formed ice crystals, (h) total water (as the sum of water vapour and ice water), and (i) cloud occurrence frequency, considering multi-year averages over the simulated period (2001–2010). Non-significant values are shaded in grey."*

## Technical comments

- Table 1 could be removed. You can refer to Table 1 in Beer et al, 2022.

Table 1 shows some additional information that was not shown in the respective Table in Beer et al. (2022). Therefore, we think it is necessary to include this table here.

- I would suggest to rename the Sec. 3 to “Model dependencies and uncertainties”

As this section specifically focuses on the dependency on the model resolution and as additional uncertainties are discussed in Sect. 4.4, we think the naming “Model resolution dependencies” is appropriate here.

- I would rather split Table 2 into two tables: 1) reference table with all the specific reference cases (not only the homogenous freezing), adding the reference label in each figure’s caption and 2) the global model simulations performed. This will rather simplify the results interpretation.

Thank you for the suggestion. We agree, that the different reference case for the case of the ammonium sulfate effect should be highlighted. We already mentioned this in the text, but now also state it explicitly in Table 2 (see the text quotes below). Despite the ammonium sulfate effect (and the effect of glassy organics), all INP effects analyzed in the present study consider a baseline with purely homogeneous freezing as a reference. Therefore, we think an additional table is not necessary here.

*(Table 2 caption) “[...] The homogeneous freezing reference cases are marked in bold. An exception are the simulations that consider AmSu (gIPOM) in addition to DU and BC (simulations F-CEN-DBA, F-CEN-DBG; see below), which consider the simulation with DU and BC as the reference case (simulation F-CEN-DB). [...]”*

*(line 293) “This is calculated as the difference between a simulation including AmSu, DU and BC INPs, and a simulation including only heterogeneous freezing on DU and BC.”*

- Figure 5 includes as reference case the “heterogeneous freezing on DU and BC” and not the “only homogeneous freezing”, this should be highlighted to avoid misinterpretation and included in the aforementioned reference table.

Thank you for pointing this out. We included an additional note in the figure caption and also mention this in Table 2 (see also our reply to the previous comment).

*(Fig. 5 caption) “... Note the different reference case with respect to Fig. 4.”*

- For Figure 7 the reference case for each RF estimation is missing. “Pure homogeneous freezing” should be added to the caption.

Thank you. We added this information to the figure caption.

*(Fig. 7 caption) “Multi-year global averages (years 2001–2010) of changes in [...] due to the total INP-cirrus effect, considering the difference with respect to the purely homogeneous freezing case, for different values of the vertical velocity...”*