Response to Anonymous Referee #2

egusphere-2025-5850: "Global Modeling of Ice Nucleating Particles of Multiple Aerosol Species and Associated Cloud Radiative Effects" by K. Kawai, Z. Ren, and H. Matsui

Thank you very much for carefully reading our manuscript and providing valuable comments. We have revised the manuscript by taking your comments into account. Below, we describe our point-by-point responses to your comments. A revised manuscript with tracked changes has been uploaded.

Referee's comment 2-1:

Lines 21 – 26: Are there studies showing how increasing the ice fraction decreases cloud lifetime and cloud fraction due to the higher fall speeds of ice particles? This will affect the CRE. If so, this process with references should be mentioned. Relevant references might be Mitchell et al. (2008, GRL) and Eidhammer et al. (2017, J. Climate, p. 618).

Response:

Thank you for suggesting these references. An increase in the ice fraction in mixed-phase clouds can lead to a reduction in cloud lifetime and cloud fraction because ice crystals generally have larger sizes and higher falling speeds than water droplets. These characteristics of ice crystals enhance formation of precipitation and the removal of condensate. This process further influences cloud radiative effects. We have added this explanation with the suggested references to the Introduction as follows (Lines 27–30): "*This shift toward the ice phase can decrease cloud water content and promote formation of precipitation and removal of condensate because ice crystals generally fall faster than liquid droplets (Mitchell et al., 2008; Eidhammer et al., 2017). Because this process can reduce cloud lifetime and cloud fraction, it can influence Earth's radiative balance through aerosol-cloud interactions (Shi and Liu, 2019; Storelvmo, 2017).*"

Eidhammer, T., Morrison, H., Mitchell, D., Gettelman, A., and Erfani, E.: Improvements in

Global Climate Model Microphysics Using a Consistent Representation of Ice Particle Properties, J. Climate, 30, 609–629, https://doi.org/10.1175/JCLI-D-16-0050.1, 2017.

Mitchell, D. L., Rasch, P., Ivanova, D., McFarquhar, G., and Nousiainen, T.: Impact of small ice crystal assumptions on ice sedimentation rates in cirrus clouds and GCM simulations, Geophys. Res. Lett., 35, L09806, https://doi.org/10.1029/2008GL033552, 2008.

Referee's comment 2-2:

Lines 41 – 43: Righi et al. (2025, ACP) may be relevant here since they show BC from aviation is not a significant INP.

Response:

Based on your comment, we have added Righi et al. (2025) to the sentence as follows (Lines 47–49): "*Black carbon (BC), a product of incomplete combustion, has also been identified as a potential source of INPs, although its ice nucleating ability is lower than that of other aerosol species (Bond et al., 2013; Kanji et al., 2017; Righi et al., 2025).*"

Righi, M., Testa, B., Beer, C. G., Hendricks, J., and Kanji, Z. A.: Aviation soot interactions with natural cirrus clouds are unlikely to have a significant impact on global climate, Atmos. Chem. Phys., 25, 18341–18353, https://doi.org/10.5194/acp-25-18341-2025, 2025.

Referee's comment 2-3:

Table 1: Please add median particle size to Table 1. This will make it clearer that the greater mass concentration of dust translates to a higher INP number concentration. (For example, anomalously large INPs may dominate the mass concentration but not the number concentration.)

Response:

Based on your comment, we have added the particle sizes of aerosol types that act as INPs to Table 1 as follows:

Table 1. *Aerosol species and types acting as INPs in this study, and data sources for their emissions and ice nucleating abilities.*

Aerosol species	*Aerosol type*	*Emission*	*Ice nucleating ability*
Dust	*Arctic dust (39 nm–10 μm)*	*Online (Zender et al., 2003; Kok et al., 2014)*	*Tobo et al. (2019); Kawai et al. (2023)*
	Non-Arctic dust (39 nm–10 μm)		*DeMott et al. (2015)*
Bioaerosols	*Bacteria (1 μm)*	*Offline (Hoose et al., 2010)*	*Diehl and Mitra (2015)*
	Fungal spores (5 μm)		*Hummel et al. (2018)*
	Pollen (30 μm)		*Diehl and Mitra (2015)*
MOA	*MOA (0.2 μm)*	*Online (Burrows et al., 2013; Wilson et al., 2015)*	*Wilson et al. (2015)*
BC	*Biomass burning BC (39 nm–10 μm)*	*Dataset (van Marle et al., 2017)*	*Schill et al. (2020)*

In addition, the size distribution of emitted dust particles is based on Kok (2011). We explain this point in Section 2.1.1. as follows (Lines 122–123): "*The size distribution of emitted dust particles is based on Kok (2011).*" The size distribution of emitted BC particles is based on Matsui et al. (2022). We have added this point to Section 2.1.4 as follows (Lines 165–166): "*BC emissions are assumed to have number median diameters of 70 nm for anthropogenic sources and 100 nm for biofuel and biomass burning sources, with a geometric standard deviation of 1.8 (Matsui et al., 2022).*"

Matsui, H., Mori, T., Ohata, S., Moteki, N., Oshima, N., Goto-Azuma, K., Koike, M., and Kondo, Y.: Contrasting source contributions of Arctic black carbon to atmospheric concentrations, deposition flux, and atmospheric and snow radiative effects, Atmos. Chem. Phys., 22, 8989–9009, https://doi.org/10.5194/acp-22-8989-2022, 2022.

Referee's comment 2-4:

Lines 89 – 91: Does this imply that the INP number concentration = the ice crystal number concentration (not the ice particle number concentration that is affected by aggregation)? More specifically, how are INPs defined? Do all INPs form ice crystals under favorable conditions? Or is there a probability, like 10%, that an INP will form an ice crystal under favorable conditions? If the former, then INP conc. = aerosol species # conc. x probability? In either case, please clearly define INP. It appears that Table 1 provides references for the INP probabilities used in this study. Please discuss how these probabilities are used.

Response:

In this study, INPs are defined as aerosol particles that can initiate ice formation under given thermodynamic conditions. The INP number concentration of each species is calculated by multiplying the mass or number concentration of each species by the activated fraction derived from its temperature-dependent ice nucleating ability. Therefore, not all aerosol particles act as INPs; rather, only a fraction of particles become active as INPs depending on temperature. We have added this explanation to Section 2.1 as follows (Lines 90–94): "*In other words, INPs are defined as aerosol particles that can initiate ice formation under given thermodynamic conditions. The INP number concentration of each species is calculated by multiplying the mass or number concentration of each species by the activated fraction derived from its temperature-dependent ice nucleating ability. Therefore, not all aerosol particles act as INPs, and only a fraction of particles become active as INPs depending on temperature.*"

The INP number concentration does not necessarily equal the ice crystal number concentration. In the cloud microphysics scheme, both water droplets and ice crystals are prognostically treated in terms of their number concentrations and mixing ratios (Neale et al., 2012). Ice nucleation processes act to increase the ice crystal number concentration, and when the available INPs exceed the existing ice crystal number concentration, the model increases the ice crystal number concentration toward the INP number concentration. We have added this explanation to Section 2.1 as follows (Lines 98–104): "*In the cloud microphysics scheme, both water droplets and ice crystals are prognostically treated in terms of their number concentrations and mixing ratios (Neale et al., 2012). There are some ice formation pathways considered in the scheme (e.g., homogeneous freezing, immersion and condensation freezing, contact freezing, and secondary ice production), which change the number concentrations and mixing ratios of water droplets and ice crystals. The INP number concentration derived from the aerosol scheme contributes to the formation of ice crystals by increasing the number concentration of ice crystals. When the available INPs exceed the existing ice crystal number concentration, the model increases the ice crystal number concentration toward the INP number concentration.*"

Referee's comment 2-5:

Lines 110 – 113: Roughly, what are the highest latitudes sampled by MODIS? This may inform the reader which latitudes have the highest confidence.

Response:

The highest latitudes sampled by MODIS are about 45° in winter and 80° in summer for each hemisphere. We have added this information to the sentence as follows (Lines 157–159): "*Missing values at high latitudes (about >45° in winter and >80° in summer) are imputed using the average north of 30° N for the Northern Hemisphere and south of 30° S for the Southern Hemisphere.*"

Referee's comment 2-6:

Lines 119 – 121: Righi et al. (2025, ACP) also found that aviation soot has no significant impact on the INP concentration. Consider adding this reference above to help justify your practice of ignoring anthropogenic BC as an INP source.

Response:

As suggested, we have added Righi et al. (2025) to the sentence as follows (Lines 167–169): "*Because anthropogenic BC does not act efficiently as INPs (Kanji et al., 2017; Righi et al., 2025), this study does not consider its contribution as INPs.*"

Righi, M., Testa, B., Beer, C. G., Hendricks, J., and Kanji, Z. A.: Aviation soot interactions with natural cirrus clouds are unlikely to have a significant impact on global climate, Atmos. Chem. Phys., 25, 18341–18353, https://doi.org/10.5194/acp-25-18341-2025, 2025.

Referee's comment 2-7:

Lines 132 – 135: Ice nucleating ability tends to decrease with increasing temperature, but here it abruptly increases moving from -9 C to -5 C. Was there a typo or is there a physical reason for this? If the latter, please provide the reason.

Response:

These values are scaling factors applied to the ice nucleating ability of bacteria used in the Base simulation. As shown in Fig. 1f (revised version), even within the suggested temperature range, the calculated ice nucleating ability of bacteria decreases with increasing temperature. We have clarified this point as follows (Lines 182–184): "*The ice nucleating ability of bacteria used in the Base simulation was multiplied by a scaling factor of* $10^{3.2}$ *at* ≤ -35 *°C,* $10^{0.2}$ *at* -19 *°C,* $10^{-0.3}$ *at* -14 *°C,* $10^{-1.8}$ *at* -9 *°C, and* $10^{1.8}$ *at* -5 *°C, with a lognormal interpolation between these temperatures.*"

Referee's comment 2-8:

Lines 204 – 208: Same comment as for Lines 89 – 91.

Response:

Please see our Response to Referee's comment 2-4.

Referee’s comment 2-9:

Figure S8 in the Supplement: Panels marked Jan 2016 through Jul 2016 should be dated as 2017.

Response:

Thank you for pointing this out. We have corrected the year in Fig. S6 (revised version) as follows:

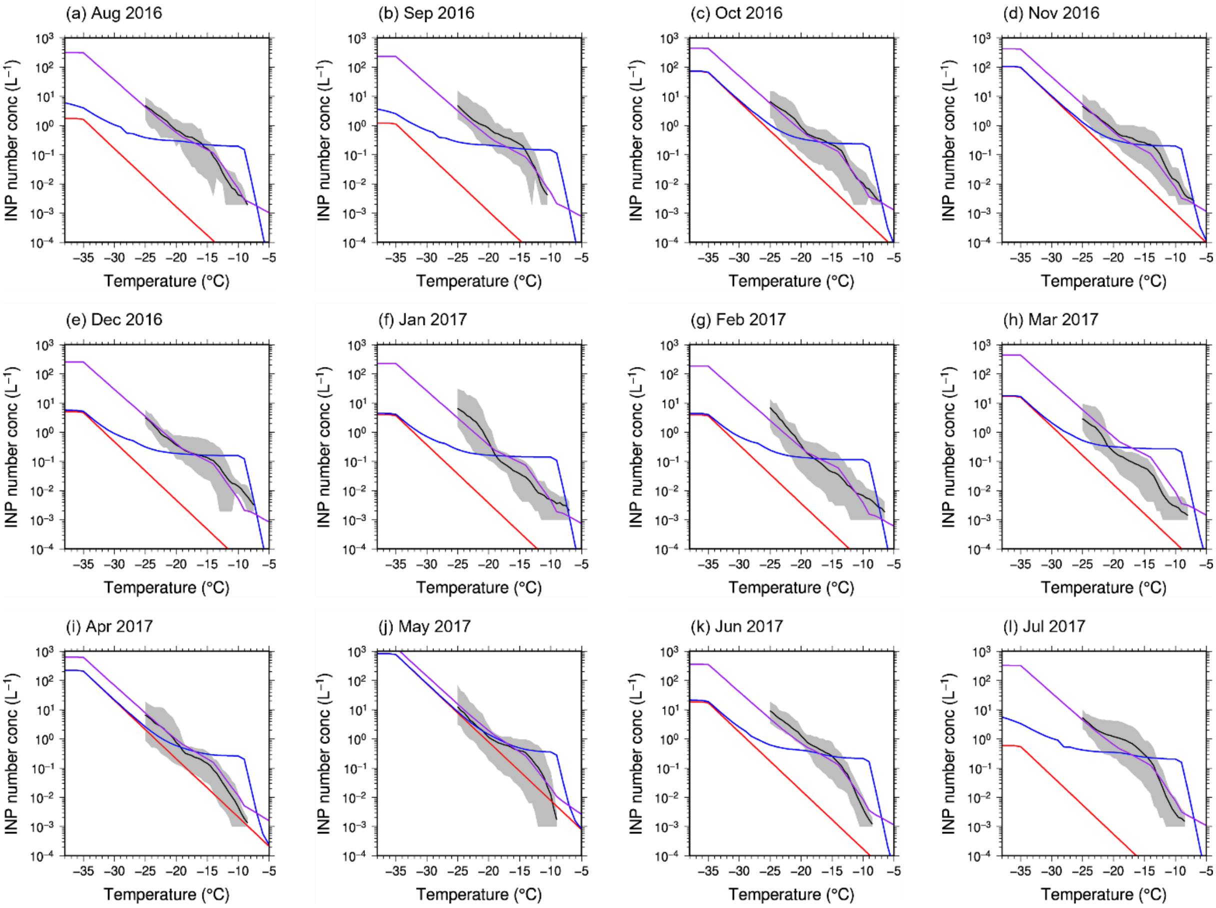

Figure S6. *Monthly mean INP number concentrations as a function of freezing temperature observed at Tokyo Skytree, Japan, from August 2016 to July 2017 (Tobo et al., 2020) (black) and simulated for the corresponding location and period for dust only (red) and for all INP sources in the Base simulation (blue) and the observationally constrained simulation (purple). Gray shading indicates the range of observed INP number concentrations.*