Response to Anonymous Referee #1

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 1-1:

Section 1: There is a recent study by Imura and Suzuki (doi:10.1175/JCLI-D-24-0335.1) that investigated climatic impact of differing INP-temperature spectra through precipitation process, which I think is relevant to the scope of this study. The authors should discuss the paper in the context described in introduction.

Response:

As suggested, we have added Imura and Suzuki (2025) to Section 1 (Introduction) as follows (Lines 30–32): "*In addition, differences in the temperature-dependent ice nucleating properties of INPs can lead to substantial variations in cloud microphysical processes and their associated climatic impacts (Imura and Suzuki, 2025).*"

Imura, Y., and Suzuki, K.: Evaluation of Climatic Impacts of Ice-Nucleating Particles through Precipitation Process with a GCM, J. Climate, 38, 2659–2677, https://doi.org/10.1175/JCLI-D-24-0335.1, 2025.

Referee's comment 1-2:

Section 2.1: It would be useful to add the plot that compares how INP number concentration depends on temperature, or the so-called INP-temperature spectra for various aerosol species treated in this study. Such a plot would be very nice to illustrate how different aerosol species newly considered in this study have different efficiencies as INPs. The plot should also include the observationally constrained function of bacteria described in Section 2.3.

Response:

As suggested, we have added plots of the ice nucleating abilities of the aerosol species considered as INPs in this study and moved Fig. S1 to Fig. 1 (revised version) as follows:

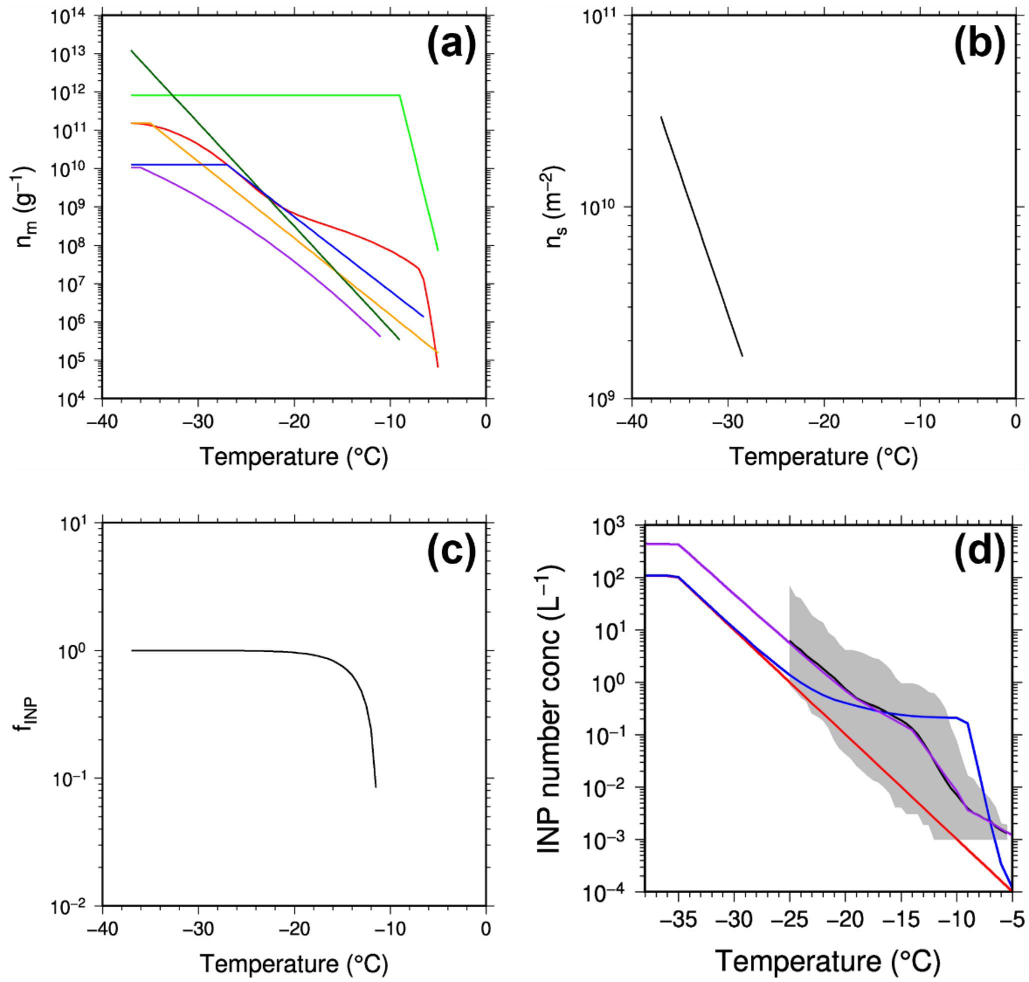

Figure 1. *Ice nucleating abilities of aerosol species and types acting as INPs in this study. (a) The red, orange, light green, green, blue, and purple lines represent the ice nucleation active site density per unit mass (n_m) of Arctic dust, non-Arctic dust, bacteria, pollen, MOA, and biomass burning BC, respectively. The n_m of non-Arctic dust and MOA were derived using the size distributions of their emitted particles assumed in our model. (b) The ice nucleation active site density per unit surface area (n_s) of Cladosporium sp. fungal spores. (c) The*

activated fraction of Mortierella alpina fungal spores. (d) Annual 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). The gray shading indicates the range of observed INP number concentrations.

Referee's comment 1-3:

Line 91-93: I don't understand what this sentence means. Why do you talk about the treatment of bioaerosols, MOA and BC here in this subsection for dust? Please clarify what "the same computational approach" means.

Response:

For dust, bioaerosols, MOA, and BC, using the ice nucleating abilities of each species, the INP number concentrations of each species are calculated online as a function of air temperature and the mass or number concentrations of each species in the presence of liquid water droplets. We have moved this explanation from Section 2.2.1 (Dust) to Section 2.1 (Global climate-aerosol model) as follows (Lines 85–90): "*Using the ice nucleating abilities of each species, the INP number concentrations of each species are calculated online as a function of air temperature (between −37 °C and −5 °C) and the mass or number concentrations of each species (both interstitial-phase and cloud-phase) in the presence of liquid water droplets. In this study, we report the number concentrations of INPs within clouds, which we equate to the grid-mean INP number concentrations multiplied by the fractions of stratus clouds. This calculation is consistent with the CAM5 cloud microphysics scheme (Gettelman et al., 2010; Morrison and Gettelman, 2008).*"

Referee's comment 1-4:

Line 104-106: Is there no temperature dependence for bioaerosols assumed here?

Response:

Thank you for your comment. In our treatment of bioaerosols, only a prescribed fraction of bioaerosol particles is assumed to be capable of acting as INPs (4%, 100%, 29%, or 8%), and this fraction itself is not temperature dependent. For these bioaerosol particles, the temperature dependence of n_m or n_s (the ice nucleation active site density per unit mass or surface area, respectively) is explicitly calculated (Diehl and Mitra, 2015; Hummel et al., 2018). We have added this point to the text as follows (Lines 148–150): "*The temperature-dependent ice nucleating abilities of 4 % of bacteria (Pseudomonas syringae) and 100 % of pollen (tree pollen) are based on Diehl and Mitra (2015) (Fig. 1a). We assumed that 29 % of Cladosporium sp. fungal spores and 8 % of Mortierella alpina fungal spores act as INPs with temperature dependence following Hummel et al. (2018) (Fig. 1b and 1c).*"

Referee's comment 1-5:

Line 134-136: Do these multiplication factors mean the factors relative to the Base simulation?

Response:

Yes, these multiplication factors mean the factors relative to the ice nucleating ability of bacteria used in the Base simulation. 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 1-6:

Line 145: "between all-sky and clear-sky conditions": Is this not a "clean-sky" CRE? That is, does the cloud radiative forcing here includes the effect of light-absorbing aerosols on cloud radiative effect? Please clarify.

Response:

CRE is calculated under aerosol-containing atmospheric conditions (not "clean-sky"). However, because aerosol fields are nearly identical between two simulations (e.g., dust INPs

×10 simulation and the Base simulation), most aerosol radiative effects may cancel out.

Referee's comment 1-7:

Line 290-292: I don't understand what this sentence means. Can you explain more clearly how the fewer total INPs, more water droplets and fewer ice crystals at the temperature warmer than -10C relate to the higher sensitivity of bioaerosols than dust?

Response:

We want to show in this sentence that mixed-phase clouds typically contain relatively few ice crystals and a large amount of supercooled water droplets at temperatures warmer than approximately −10 °C where bioaerosols dominate INP activity. Under such conditions, even a small increase in INP number concentration can efficiently enhance ice formation, which in turn promotes the conversion of water droplets to ice crystals via the Wegener–Bergeron–Findeisen process. As a result, bioaerosols could exert a relatively large impact on cloud microphysical properties and radiative effects despite their smaller INP number concentrations compared to dust. We have revised the sentence to clarify this interpretation as follows (Lines 346–351): "*This difference in sensitivity might be related to the fact that, at temperatures where bioaerosols dominate INP activity (warmer than approximately −10 °C), mixed-phase clouds typically contain relatively few ice crystals and abundant supercooled water droplets. Under such conditions, an increase in INPs could efficiently enhance ice formation and promote the conversion of water droplets to ice crystals, leading to a stronger impact on cloud properties.*"

Referee's comment 1-8:

Line 294-295: Does this mean that the dust and bioaerosol contributions to overall CRE are mostly linear?

Response:

Thank you for your comment. This sentence means that the global-mean CRE in the Base simulation can be largely explained by the sum of the dust and bioaerosol contributions. However, we avoid using the term "linear" here because it could be interpreted as implying that the cloud response is proportional to changes of INP number concentrations.

Referee's comment 1-9:

Line 301-303 and Table 2: The table shows only the "All INP sources" value of CRE. Are the CREs from aerosol species other than bacteria are same between the observationally constrained and Base simulations? Namely, does the difference in CRE from the all INP sources between the two simulations (0.64 vs 0.24 Wm-2) come from only the bioaerosol-induced CRE? Please clarify.

Response:

The CREs of all aerosol species other than bacteria via INPs are almost the same between the Base and observationally constrained simulations. Although the differences in CREs between the Base and observationally constrained simulations result from the treatment of bioaerosols, this constraint should be interpreted as reflecting uncertainties in multiple factors, including not only the emission and ice nucleating ability of bacteria, but also INPs from other aerosol species and unknown sources. We explain this point in Section 3.4 as follows (Lines 364–366): "*Although we constrain the ice nucleating ability of bacteria to the INP observations in Tokyo, the differences in CREs between the Base and observationally constrained simulations may reflect uncertainties in various factors, including not only the emission and ice nucleating ability of bacteria, but also INPs from other aerosol species and unknown sources.*"

Referee's comment 1-10:

Figure 3 caption: orange -> yellow. To my eye, the color of dust looks more like yellow rather than orange.

Response:

As suggested, we have changed "orange" to "yellow" in the caption of Figure 5 (revised version) as follows (Lines 277–279): "*Figure 5. Fractions of dust (yellow), bioaerosols (green), MOA (blue), and BC (gray) in the annual and global mean vertically integrated total INP number concentrations (shown on the right) in (a) the whole atmosphere (2–1000 hPa) and (b)* *the upper (100–400 hPa), middle (400–700 hPa), and lower troposphere (700–1000 hPa).*"