

Response to Anonymous Referee #1

egusphere-2025-6214: “Impacts of Arctic warming on ice nucleating particles over recent decades: Distributions and contributions of dust, marine organic aerosols, and bioaerosols”
by Z. Ren, K. Kawai, M. Liu, and H. Matsui

We sincerely appreciate the time and effort the referee devoted to carefully reading our manuscript, as well as the constructive comments. This feedback has prompted substantial revisions, and we believe the manuscript has been considerably improved as a result. Our point-by-point responses are provided below. The reviewers' comments are shown in blue, with our replies in black. New text added to the manuscript is presented in italics.

Specific Comments

SC1 More of a clarification really. I struggle with the usage of INA as a changing variable. To me, INA is an inherent characteristic of a particle, which we know is lower at higher temperatures. However, the way I read the manuscript it sounds like the INA is changing (as in the full spectra) rather than that we simply consider a different ambient temperature at which to explore the INA at. The main problem I have is really the use of words such as “reduction and declining” when we are simply evaluating INA(T1) instead of INA(T2). In the end the same effect, but the interpretation is different. The lines mentioned below show where I have a bit of a problem with this. In Matsui et al. 2024 this is referred to the “temperature effect”, why not stick with this key word after its introduction?

L49 “reduction of aerosol INA at ambient temperature”

L55 “declining INA”

L56 “INA-driven decrease” perhaps rather → “temperature-driven versus emission driven”

L66 “decreasing INA”

We have revised the relevant descriptions to clarify that the changes in INP concentrations reflect the temperature dependence of INA under different ambient temperatures rather than changes in INA itself. We also avoid expressions such as “a reduction in INA” or “declining INA” and consistently use the term “temperature effect”.

The revised sentences are as follows:

L55 One key effect of Arctic warming is a decrease in INP concentrations in clouds, because aerosol INA is lower at higher ambient temperatures, even if aerosol abundance remains unchanged (Matsui et al., 2024).

***L60** This enhancement of emissions can cause an increase in INP concentrations in clouds that could reduce cloud reflectivity and coverage and lead to cloud radiative effects opposite to those associated with the temperature effect (hereafter, the emission effect in Matsui et al. (2024)).*

***L62** These counterbalancing responses of INPs to Arctic warming—temperature-driven decreases versus emission-driven increases—form complex feedbacks that modulate Arctic cloud-climate interactions.*

***L64** Matsui et al. (2024) have shown that, under Arctic warming over the past four decades, the increase in Arctic dust INPs driven by the emission effect has substantially offset the decrease in INPs caused by the temperature effect.*

***L71** Importantly, we investigate long-term changes of INPs in the Arctic driven by both temperature effect and emission effect.*

***L246** Arctic INPs in clouds exhibit broader vertical distributions and are more prevalent during colder seasons than Arctic aerosol concentrations because INAs are higher at lower temperatures (Fig. 4d–f).*

***L361** Changes in Arctic INPs in clouds are controlled by the balance between the increase in INPs caused by increasing emissions (emission effect) and the decrease in INPs caused by lower INA at higher temperatures (temperature effect) (Matsui et al., 2024).*

***L392** In contrast, Arctic INP concentrations in clouds decreased by 19%, 29%, and 24% as a result of the temperature effect (Matsui et al., 2024). This contrast suggests that the temperature effect has a greater influence on INP concentrations than the emission effect, except in regions where emissions increase substantially and thus outweigh the temperature effect.*

SC2 My main concern which might be more of a confusion. This is in regard to Fig.3, 5 and S6. Showing dust aerosol mass/number concentration across the full temperature spectrum makes sense, but showing a presence of INP concentration at 0°C does not. How are these INPs calculated? Any parameterisation for INPs, simplistic ones only depending on temperature as well as INAS densities are only valid within a certain temperature range making it impossible to have a presence of for example dust INPs at 0°C. Perhaps an extrapolation to warmer temperatures was done? In that case, an easy fix otherwise I am a bit confused on how these INP concentrations are obtained. Please clarify

In our simulations, INP concentrations are calculated at each model timestep (every 30 minutes) using the ambient temperature, aerosol mass or number concentrations, and cloud fraction. The INP calculation is performed for temperatures ranging from −37°C to −5°C.

The temperature contours shown in Figures 3, 5, and S6 of the original manuscript represent the 40-year mean temperature, whereas the ambient temperature used in the INP calculations varies and fluctuates over time. Therefore, even when the 40-year mean temperature is higher than -5°C , the 40-year mean INP concentration can be greater than zero if the temperature falls below -5°C at some model timesteps. The temperature contours are included to show its temporal variation and vertical distribution.

To clarify the calculation method for INPs, we have revised the description in the manuscript as follows:

L117 For each species, INP number concentrations are calculated online every 30 minutes from the mass or number concentrations of the species and ambient temperature, using a temperature-dependent activated fraction that represents its ice nucleating ability from -37°C to -5°C . To represent INPs within clouds, the grid-mean INP number concentrations are multiplied by the stratus cloud fraction at each timestep and then averaged to monthly mean values.

We have also added the following statement to the captions of Figures 4, and 6 to improve clarity.

Black lines indicate 40-year mean Arctic temperatures.

Figure 4. Because INP concentrations are calculated using the ambient temperature at each model timestep, the 40-year mean INP concentration can be greater than zero even where the 40-year mean temperature shown in the figure exceeds -5°C .

SC3 While the focus is on the species that are locally emitted, the interesting comparison is really with the long-range transported INPs. I think these should be shown both spatially and temporally followed by the comparison to the local species.

While Arctic INPs dominate the INPs in the Arctic lower troposphere (> 730 hPa) from summer to fall (Fig. 6), non-Arctic aerosols — originating from regions south of 60°N and transported into the Arctic — contribute more than 90% of the total INPs in the Arctic upper troposphere (< 500 hPa) throughout the year. In particular, during spring and winter, their influence extends into the lower troposphere (Fig. R1), with non-Arctic aerosols accounting for 57% and 54% of total INPs in the lower troposphere (> 730 hPa), respectively (Fig. R2). Among the non-Arctic aerosol species, transported dust dominates the INPs in the upper troposphere throughout the year, non-Arctic MOA contributes approximately 30% of the INPs in the middle troposphere during winter, and non-Arctic bioaerosols primarily contribute to INPs at temperatures between -20°C and -10°C (Fig. R3).

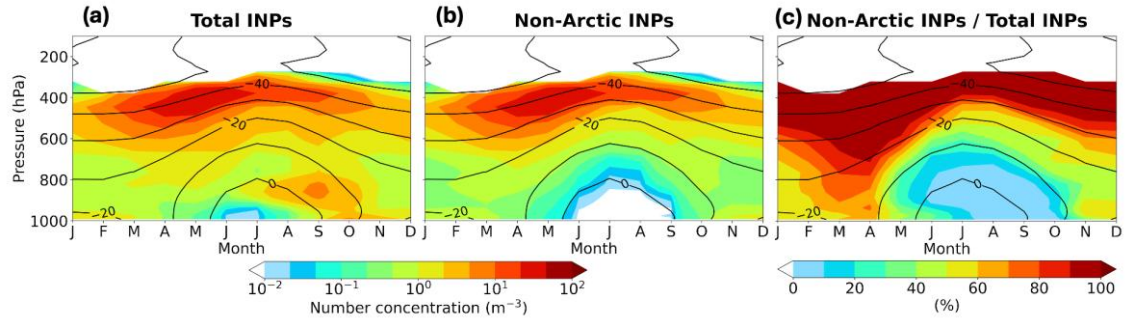


Figure R1. Vertical distributions and temporal variations of (a) total (Arctic + non-Arctic) INPs, (b) non-Arctic INPs, and (c) the contribution of non-Arctic INPs to total INPs. Data are averaged over the Arctic region during 1981–2020. Black lines indicate 40-year mean Arctic temperatures.

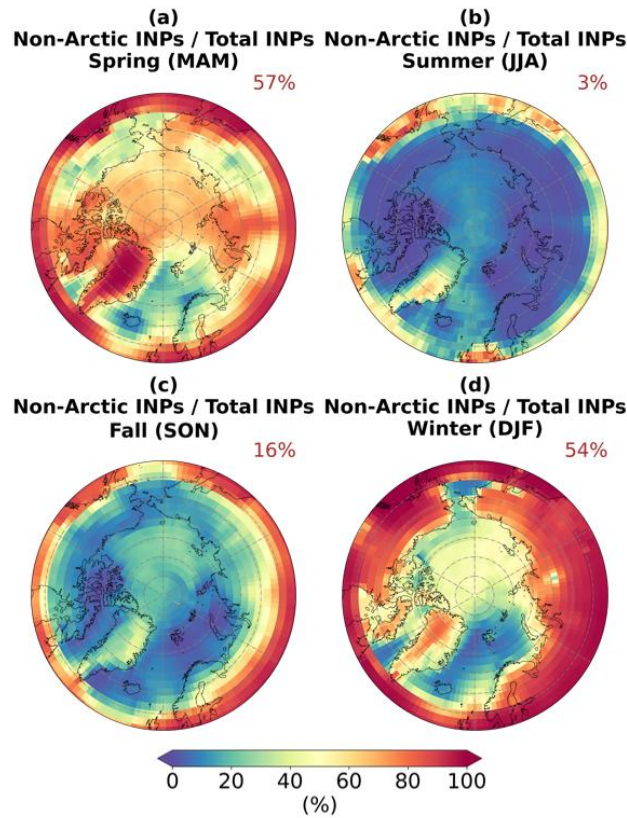


Figure R2. Spatial distributions of the contribution of non-Arctic INPs to total INPs in the Arctic lower troposphere (> 730 hPa) for (a) spring (MAM), (b) summer (JJA), (c) fall (SON), and (d) winter (DJF), averaged over 1981–2020. The numbers in the upper-right corner of each panel indicate the 40-year mean values averaged over the Arctic lower troposphere.

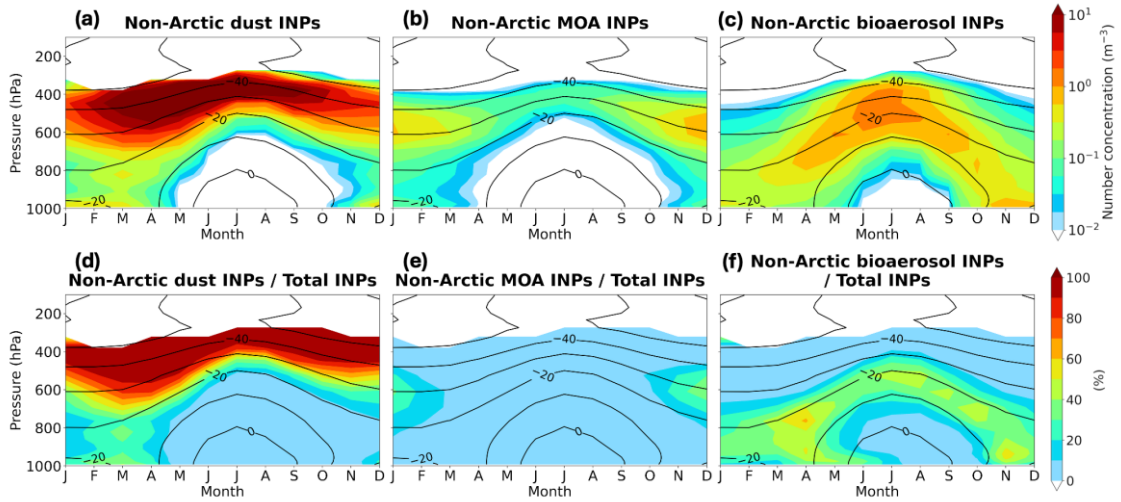


Figure R3. Vertical distributions and temporal variations of (a–c) INP number concentrations and (d–f) contributions to total INPs from non-Arctic dust, non-Arctic MOA, and non-Arctic bioaerosols, respectively. Data are averaged over the Arctic region during 1981–2020. Black lines indicate 40-year mean Arctic temperatures.

Since this study focuses on aerosols emitted locally in the Arctic, an extensive discussion of regions outside the Arctic would be beyond the scope of the manuscript. We have therefore added Figure R2 to the Supplementary Information as Fig. S10 and included a brief description in the manuscript as follows:

***L283** In contrast, non-Arctic INPs dominate over Greenland and continental regions during these seasons.*

***L287** In the upper tropospheric clouds at around -40°C to -30°C , total INPs are mainly from aerosols transported from middle and low latitudes throughout the year, with Arctic INPs contributing less than 10% in the middle and upper tropospheric clouds (Fig. 6d).*

SC4 The authors explore the parameterisation for bacteria, which is very useful as this species is yet to be well defined in modelling. But what about the parameterisation for dust? The authors use a different one outside and inside the Arctic but how much does this impact the results? What about other parameterisations for dust and MOA? When parts of the conclusions state the importance of choosing the correct parameterisation I believe more exploration of this topic is warranted. Easiest option would be to add more parameterisation options to the offline calculations performed for Section 3.1.

We have evaluated different parameterizations for dust INPs in our previous studies. Kawai et al. (2023) examined the differences between two dust INP parameterization schemes, DeMott et al. (2015) and Tobo et al. (2019). The results show that applying the DeMott et al. (2015) parameterization to Arctic aerosols tends to underestimate observed

INPs in the Arctic, while the Tobo et al. (2019) parameterization generally yields better agreement with observations (Fig. R4).

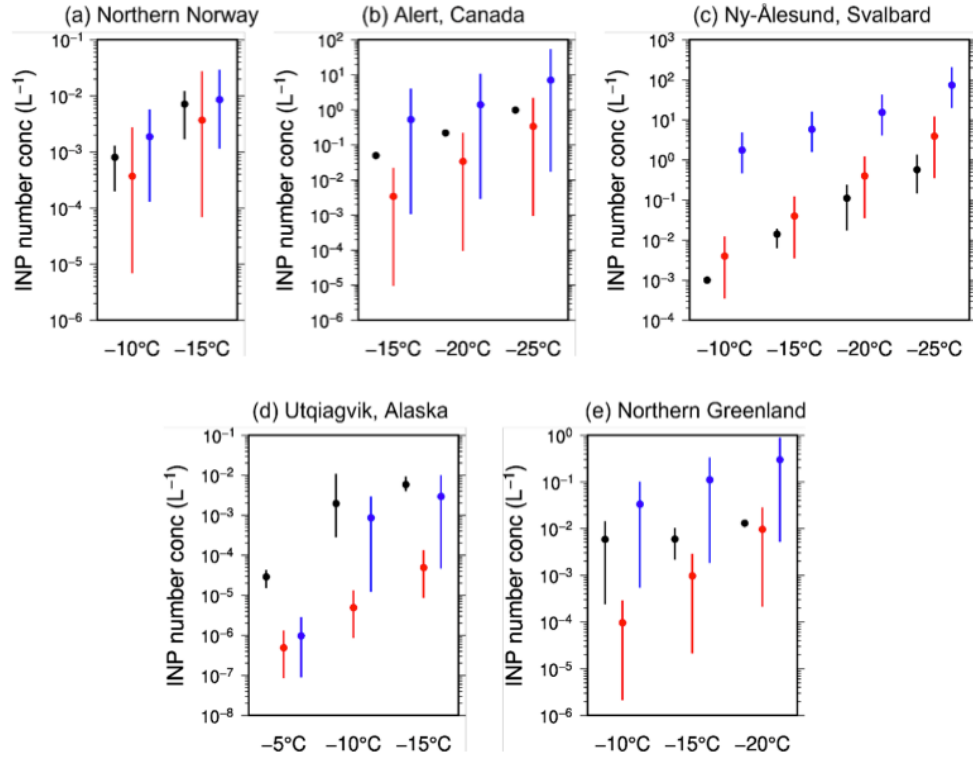


Figure R4. Figure S6 from Kawai et al. (2023). Comparisons between INP observations in (a) northern Norway (Conen et al., 2016), (b) Alert, Canada (Mason et al., 2016), (c) Ny-Ålesund, Svalbard (Tobo et al., 2019), (d) Utqiagvik, Alaska, and (e) northern Greenland (Wex et al., 2019) in the Arctic region during seasons including summer and fall (black) and the BASE and HIGH simulations (red and blue, respectively) for given temperatures (Table S3). The dots and bars represent the averages and ranges of INP number concentrations, respectively. For the simulations, the ranges of dust INP number concentrations averaged in the corresponding month(s) for the years 2010–2019 are shown. (d, e) Observation data during summer and fall (June–November) were extracted and averaged.

Kawai et al. (2021) examined the sensitivity of simulated INP number concentrations to different dust INP parameterizations (DeMott et al., 2015; Niemand et al., 2012; Ullrich et al., 2017) using offline calculations and compared the calculated INP concentrations with observations at the Tokyo Skytree, focusing on magnitude and temperature dependence. The results showed that the parameterization of DeMott et al. (2015) best reproduced the observed INP number concentrations (Fig. R5).

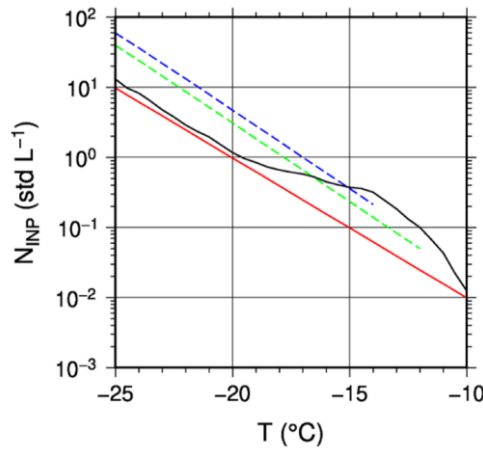


Figure R5. Figure S8 from Kawai et al. (2021). Temperature dependence of observed (black lines) and simulated (red lines) INP number concentrations at Tokyo Skytree in Japan during May 2017. Note that the observed and simulated data are referenced to Japan Standard Time (UTC + 9 hours) and UTC, respectively.

Accordingly, we have added the following description to the manuscript.

L126 Our previous studies evaluated multiple dust INP parameterizations (DeMott et al., 2015; Niemand et al., 2012; Tobo et al., 2019; Ullrich et al., 2017) against observations from the Tokyo Skytree and Arctic field campaigns, and supported the use of these two parameterizations (Kawai et al., 2021, 2023, 2026).

We have not yet applied or evaluated alternative MOA INP parameterizations. The present study does not aim to systematically compare different INP parameterizations, but rather to provide a first-order estimate of three species of Arctic INPs in clouds, quantify their contributions and seasonal variations, and characterize changes in INPs under Arctic warming. We have therefore revised or removed statements related to the comparison of INP parameterizations and added the following sentence.

L401 Overall, this study provides a first-order estimate of Arctic INPs in clouds from dust, MOA, and bioaerosols, illustrating their relative contributions and seasonal variations.

SC5 Section 3.5. I'm not sure what this contributes to the story line. The LowBac and Base were explored against observations which is very useful to see, but here I do not see many new results presented in this section. I furthermore get the feeling this is also from the authors side as the figures are mostly in the supplementary information. Thus, perhaps a shorter section could be made, starting with the lines L317-325 and discussing the LowBac plots in Fig. 8. To me these sentences (or variations of them) might be worth keeping:

“The number concentration of Arctic bioaerosol INPs in the Arctic lower troposphere in the LowBac simulation is less than 2% of that in the Base simulation (Fig. S3i).”

“While the magnitudes of the concentrations differ considerably, the rates of reduction over the four decades are nearly identical in the Base and LowBac simulations.”

“Overall, compared to the Base simulation, the LowBac simulation produces much lower Arctic bioaerosol INP concentrations that lead to lower concentration of Arctic INPs and total INPs. The result is better agreement with the observations in Northern Norway and Alaska, although both simulations perform well at the other three observation sites.”

In response to the reviewer’s comment, we moved the figures related to LowBac in Section 3.5 to the Supplementary Information and retained only the key conclusions in the main text, as follows:

L135 We mainly show the results of the Base simulation in the main text, while the results of the LowBac simulation are provided in the Supplementary Information as a sensitivity analysis.

L232 Compared with the Base case, the LowBac case produces much lower Arctic bioaerosol INP concentrations in clouds—less than 2% of the Base case values in the Arctic lower troposphere (Fig. S6i)—leading to lower Arctic INP and total INP concentrations in clouds (Fig. S7).

L343 The LowBac case shows a similar rate of reduction over the four decades, although the INP concentrations are considerably lower than in the Base simulation (Fig. S13i).

We also revised Figure 9 (original Figure 8) and moved the remaining panels to the Supplementary Information.

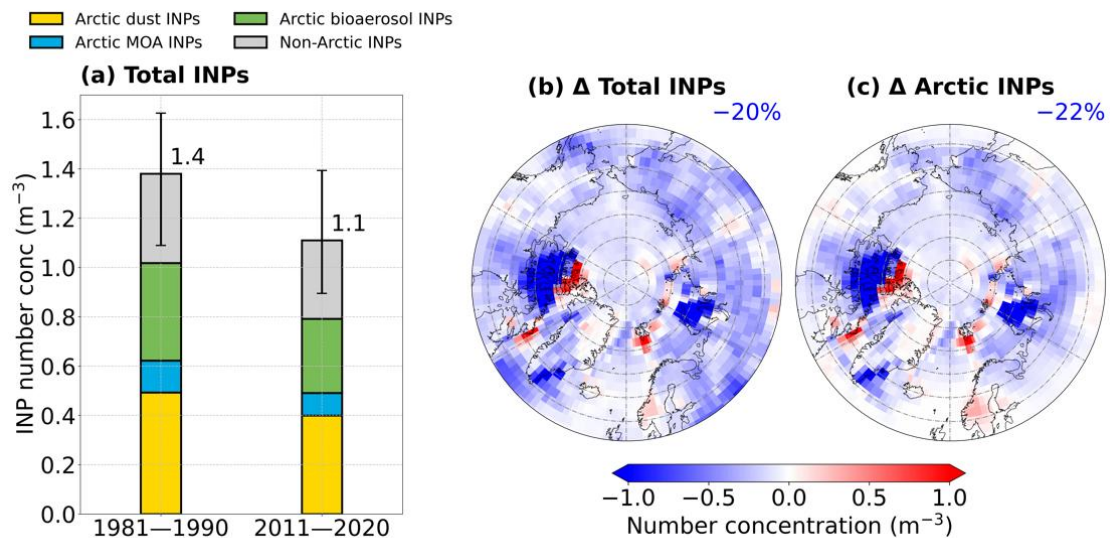


Figure 9. Decadal changes in INP number concentrations in Arctic lower tropospheric clouds (> 730 hPa) between 1981–1990 and 2011–2020. (a) Mean INP number concentrations for the two periods. (b–c) Spatial distributions of changes in INP number concentrations in clouds for (b) total INPs and (c) Arctic

INPs (Arctic dust INPs + Arctic MOA INPs + Arctic bioaerosol INPs). In panel (a), Arctic dust, Arctic MOA, Arctic bioaerosols, and non-Arctic aerosols (i.e., aerosols emitted south of 60°N) are shown in yellow, blue, green, and grey, respectively. Error bars represent interannual variability (minimum–maximum ranges) for each period. In panels (b–c), the numbers in the upper right corner indicate percentage changes in mean values between the two periods.

Line-by-line

L19-22 So I struggled to understand these sentences first time I read them. Perhaps it would be more clear to start the “Nevertheless” sentence rather with a statement on the increased temperature under Arctic warming, which leads to a reduction in INP concentration as it is highly temperature dependent.

We revised the wording as suggested.

***L20** In contrast, higher temperatures reduce the abundance of aerosol particles acting as INPs in Arctic lower tropospheric clouds because of the strong temperature dependence of aerosol ice nucleating ability. The balance between this temperature-driven decrease and the emission-driven increase results in a net 19–29% decrease in INP concentrations in Arctic lower tropospheric clouds.*

L29 Here, the authors are referring to the WBF process, which first of all should be properly cited (Wegener, 1911; Bergeron, 1928; Findeisen, 1938) and also mentioned that this is the process the authors are referring to. Furthermore, this is an elusive process that requires certain environmental and microphysical conditions and is not a process that automatically occurs in mixed-phase clouds, thus a more hypothetical language (clouds “may” shift, etc) should be used

We have revised the wording as suggested.

***L32** According to the Wegener–Bergeron–Findeisen (WBF) process, once ice nucleation is initiated by INPs, water vapor evaporates from surrounding liquid droplets and deposit onto growing ice crystals (Bergeron, 1935; Findeisen, 1938; Wegener, 1911). Through this process, clouds may shift from being dominated by many small liquid droplets to containing fewer but larger ice crystals (Lamb and Verlinde, 2011).*

L35 “in Arctic aerosol-cloud modelling” needs citation; some options;

We have added the citation as suggested.

***L38** However, ice nucleation mediated by INPs remains one of the most inadequately*

understood processes in Arctic aerosol-cloud modeling (Fridlind and Ackerman, 2017; Morrison et al., 2009; Stevens et al., 2018; Wallentin et al., 2025, 2026).

L44 Also specify the large temperature dependence

We have revised the wording as suggested.

***L48** These aerosol species differ in their ice nucleation active site densities either per unit mass (nm) or per unit surface area (ns), hereafter referred to as ice nucleating ability (INA), which exhibits a strong temperature dependence (Demott et al., 2015; Diehl and Mitra, 2015; Hummel et al., 2018; Tobo et al., 2019; Wilson et al., 2015).*

L47 “at higher subzero temperatures” Higher than what? Dust? Please specify

We revised the wording and clarified that "relatively high subzero temperatures" refers to temperatures above -15°C .

***L51** For example, dust emitted in the Arctic (Arctic dust) has been shown to exhibit higher INA than other mineral dust types (Tobo et al., 2019), whereas bacteria maintain high INA at relatively high subzero temperatures ($> -15^{\circ}\text{C}$) (Diehl and Mitra, 2015).*

L50 Cite this sentence (Matsui 2024). Also, why is this INP_cloud variable introduced? It is not used later in the manuscript

We replaced "INP_cloud" with "INP" and added the citation. We also emphasized at key points in the manuscript that our focus is on INPs within clouds.

***L55** One key effect of Arctic warming is a decrease in INP concentrations in clouds, because aerosol INA is lower at higher ambient temperatures, even if aerosol abundance remains unchanged (Matsui et al., 2024).*

Section 2 Methods:

Kawai et al also mentions for MOA “Missing values at high latitudes are imputed using the average north of 30° N for the Northern Hemisphere and south of 30° S for the Southern Hemisphere.” their line 112. What does this imply for the setup used here? How many values are missing within the studied domain and temporal range?

The highest latitudes sampled by MODIS are approximately 45° in winter and 80° in

summer in each hemisphere. Thus, POC values are missing poleward of these latitudes. These missing values are imputed using the average POC north of 30° N in the Northern Hemisphere and south of 30° S in the Southern Hemisphere, following Kawai et al. (2026). This treatment provides POC estimates for high-latitude regions where MODIS retrievals are unavailable and therefore affects MOA emission calculations in the Arctic.

We have added the following descriptions to the manuscript.

***L108** At high latitudes where MODIS POC data are unavailable, missing values are imputed using the average POC north of 30° N in the Northern Hemisphere and south of 30° S in the Southern Hemisphere, following Kawai et al. (2026).*

***L211** For Arctic MOA emissions, our estimate over 66–90°N (0.15 Tg y⁻¹) is approximately 2.6 times the value reported by Leon-Marcos et al. (2026) (0.057 Tg y⁻¹). This difference may partly be related to our use of average POC values at high latitudes where MODIS POC data are unavailable (Section 2.2).*

L73 “these three are important contributors to INPs” needs proper citation for each species

We have added citations as suggested by the reviewer.

***L86** Dust, MOA and bioaerosols are important contributors to INPs (Tobo et al., 2019; Wilson et al., 2015; Kawana et al., 2024; Pereira Freitas et al., 2023; Šantl-Temkiv et al., 2019).*

L84 Section 2.2 This section could use some more clarifications, a table listing the included aerosol species, its emission parameterisation, and its INP parameterisation would be good.

We have added the following sentence and Table 1, which summarizes the aerosol species included in the model and their emission and INP parameterizations.

***L95** Table 1 summarizes the aerosol emission schemes and INP parameterizations used in this study.*

Table 1: The treatment of emissions and ice nucleating abilities of the aerosol species in this study.

Aerosol species	Aerosol type	Emission	Ice nucleating ability
Dust	Arctic dust	Online (Zender et al., 2003; Kok et al., 2014)	Tobo et al. (2019); Kawai et al. (2023)

	Non-Arctic dust		DeMott et al. (2015)
Bioaerosols	Bacteria		Base: Diehl and Mitra (2015)
		Offline (Hoose et al., 2010)	LowBac: Hummel et al. (2018)
	Fungal spores		Hummel et al. (2018)
	Pollen		Diehl and Mitra (2015)
MOA	MOA	Online (Burrows et al., 2013; Wilson et al., 2015)	Wilson et al. (2015)
BC	Biomass burning BC	CMIP6 emission dataset (van Marle et al., 2017)	Schill et al. (2020)

Especially mention within which temperatures the parameterisations are active (to understand Fig. 3).

The calculation of INPs is performed within the temperature range of -37°C to -5°C . We have added the details as suggested.

***L117** For each species, INP number concentrations are calculated online every 30 minutes from the mass or number concentrations of the species and ambient temperature, using a temperature-dependent activated fraction that represents its ice nucleating ability from -37°C to -5°C .*

Additionally, but not required, would be a figure showing the INP parameterisations and their dependency with temperature.

The temperature dependence of the ice nucleating abilities of the aerosol species and types considered in this study is shown in Figure 1 of Kawai et al. (2026) (Fig. R6). Since this figure has already been presented in Kawai et al. (2026), we have not included it again in this manuscript. We have clarified in the manuscript that these temperature-dependent relationships are shown in Kawai et al. (2026).

***L122** As outlined below, species-specific INP parameterizations are used in this study to represent the temperature dependence of INA (Kawai et al., 2026).*

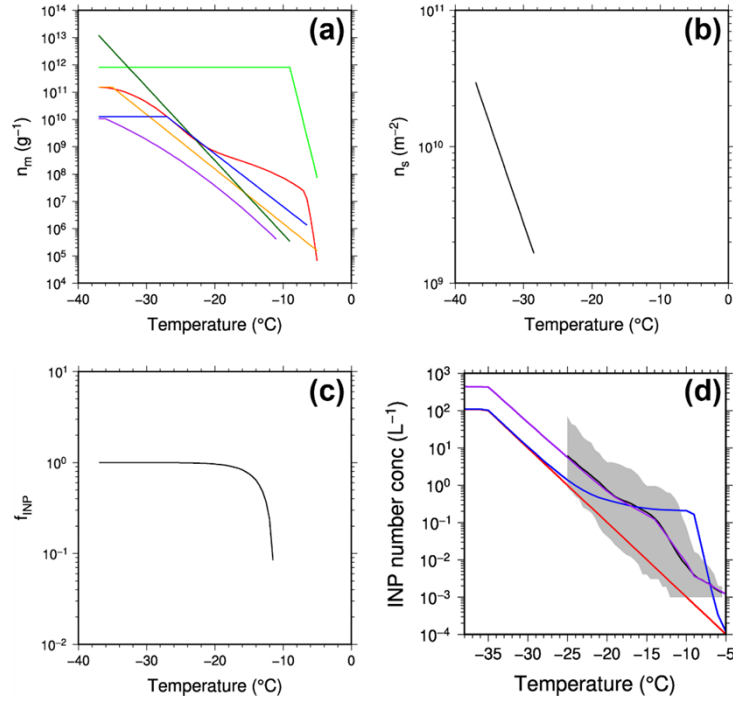


Figure R6. Ice nucleating abilities of aerosol species and types acting as INPs in this study. (a) The red, orange, light green, green, blue, and purple lines represent the ice nucleation active site density per unit mass (n_m) of Arctic dust, non-Arctic dust, bacteria, pollen, MOA, and biomass burning 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.

Furthermore, splitting the aerosol emission and INP parameterisation sections might improve readability.

As suggested, we split the original Section 2.2 "Aerosol emission and INP parameterizations" into Section 2.2 "Aerosol emission parameterizations" and Section 2.3 "INP parameterizations."

Bit more information on the included species is also required here. For example what are the assumed size bins for dust and sea salt?

In response to this comment, we have added information on the aerosol size distributions in the following four places in the manuscript.

L80 The model resolves aerosol particles with dry diameters from 1 nm to 10 μm

into 12 size bins (excluding bioaerosols and MOA), and explicitly represents a wide range of aerosol processes and their roles in ice nucleation.

L98 *The size distribution of emitted dust particles is adopted from the work of Kok (2011). In our model, this size distribution is applied to dust particles ranging from 39 nm to 10 μm .*

L99 *Bioaerosol emissions are calculated following the approach of Hoose et al. (2010), considering only terrestrial sources, with separate emission fluxes calculated for pollen, bacteria, and fungal spores. The emitted particle diameters are assumed to be 30 μm , 1 μm , and 5 μm , respectively.*

L105 *MOA emissions are calculated using an emission scheme based on Burrows et al. (2013) and Wilson et al. (2015), in which MOA emissions are linked to sea spray emissions (Mårtensson et al., 2003; Monahan et al., 1983). The emitted MOA particles are assumed to have a diameter of 0.2 μm following Burrows et al. (2013).*

L91 Perhaps mention again here that the land is actively simulated and that this is not parameterised. Could the authors mention how often the feedback from the land model is performed, i.e. how often is there a change in emission due to more exposed land areas?

The land model is run with a 30-minute timestep, consistent with that of the CAM simulation, and thus aerosol emissions respond to changes in snow and sea ice cover every 30 minutes. We have revised this description and added further details.

L95 *The emissions of dust, MOA, and bioaerosols are calculated every 30 minutes based on meteorological and surface conditions (Kawai et al., 2026).*

L93 Sea spray emissions instead of sea salt?

We revised it as suggested.

L105 *MOA emissions are calculated using an emission scheme based on Burrows et al. (2013) and Wilson et al. (2015), in which MOA emissions are linked to sea spray emissions (Mårtensson et al., 2003; Monahan et al., 1983). The emitted MOA particles are assumed to have a diameter of 0.2 μm following Burrows et al. (2013).*

L99 Every time the authors mention the aerosols included the species change. There has not been any mention of BC before. Make sure the correct ones are listed or specify that black carbon is not included in this study (L42, L62, L72, L85, and probably more)

In this study, we mainly focus on dust, MOA, and bioaerosols (including pollen, bacteria,

and fungal spores) and their INPs. BC-derived INPs are also calculated in the model and included in the total INPs (Kawai et al., 2026), but are not analyzed separately in this study because their contribution is negligible.

We have revised the description and added the relevant information on black carbon accordingly.

L121 Although black carbon INPs are calculated in the model and included in the total INPs (Kawai et al., 2026), they are not specifically investigated in this study because their contribution is negligible.

L103 The usage of DeMott 2015 for dust might need to be justified. Why not use newer parameterisations? And specify whether this is assuming the dust is mineral dust (in comparison to fertile soil dust which is quite a debated topic currently?) Also, how much difference does this produce? Has anyone studied the impact? (SC4)

The INP parameterization of DeMott et al. (2015) is used for non-Arctic dust because it is widely adopted in global aerosol-climate models (e.g., Vergara-Temprado et al., 2017). Kawai et al. (2021) examined the sensitivity of simulated INP number concentrations to different dust INP parameterizations (DeMott et al., 2015; Niemand et al., 2012; Ullrich et al., 2017), and compared the calculated INP concentrations with observations at the Tokyo Skytree, focusing on their magnitude and temperature dependence. The results showed that the parameterization of DeMott et al. (2015) best reproduced the observed INP number concentrations. Kawai et al. (2026) also adopted the parameterization of DeMott et al. (2015) for non-Arctic dust INPs and showed good agreement with observational data. Based on these previous evaluations, we adopt the parameterization of DeMott et al. (2015) in this study.

We have added the following sentences to the manuscript.

L125 The INP concentrations are calculated following Kawai et al. (2023) for Arctic dust and DeMott et al. (2015) for non-Arctic dust. Our previous studies evaluated multiple dust INP parameterizations (DeMott et al., 2015; Niemand et al., 2012; Tobo et al., 2019; Ullrich et al., 2017) against observations from the Tokyo Skytree and Arctic field campaigns, and supported the use of these two parameterizations (Kawai et al., 2021, 2023, 2026).

L118 What does this mean for the simulations? Does the SST and sea ice cover not change with time? Perhaps explain this a bit more in detail

We have clarified that SST and sea ice fraction vary with time during the simulation. CAM-ATRAS uses the merged HadISST+OISST monthly time-varying datasets as

boundary conditions for 1980–2020.

We have added the following statement to the manuscript:

***L144** Sea surface temperature and sea ice data were prescribed using merged monthly Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) and NOAA 1/4° Daily Optimum Interpolation Sea Surface Temperature (OISST) datasets (Hurrell et al., 2008), allowing them to vary throughout the simulation period.*

L128 “the Base case applied the Diehl and Mitra (2015) parameterization for bacterial INPs, while the LowBac case adopted the Hummel et al. (2018) parameterization, which assumes lower INA for bacteria”. Not needed, simply refer to the table (comment on L84).

We have revised the relevant content as suggested.

***L154** In the Base and LowBac cases, total INPs were calculated using the INP parameterizations described in Section 2.2 (Table 1), while in the NoBac case, bacterial INPs were excluded from the Base calculation.*

L132 Black carbon? Reading the rest of the paper it does not look like this is included? If it is then the INP parameterisation for BC has not been reported. A brief discussion on the inclusion of this species for evaluation in the mixed-phase range would be beneficial, as other studies claim it has a small impact. Justify its inclusion perhaps by stating these other studies. Also, in Kawai submitted work seems the BC has no impact? Perhaps comment on this already in Sect. 2.2.

Please see our response to the comment on L99.

L133 “temperatures” As in the ambient temperature during collection or the activation temperature range of the measurements?

We selected temperatures that are consistent with the observed activation temperatures. Therefore, the following statement has been added to the end of Section 2.4 to clarify the choice of temperatures.

***L158** For each of these offline calculations, temperatures were selected to match the observed activation temperatures, and INP number concentrations were averaged over the period 2010–2019 for the months corresponding to each observational dataset.*

Section 3.1 I would be interested in seeing the results from MOSAiC included here as the authors are exploring high latitude stations, Creamean et al 2022 <https://www.nature.com/articles/s41467-022-31182-x> and Barry et al 2025 <https://doi.org/10.5194/acp-25-11919-2025> are both exploring this data in detail. Granted the full year of 2020 was included in the simulation?

As suggested by the reviewer, we evaluated the simulated INP concentrations against observations from the MOSAiC campaign (Creamean et al., 2022). *We used monthly mean INP concentrations from October 2019 to October 2020. For the model comparison, we extracted monthly mean aerosol concentrations from all model grid cells crossed by the ship track in each month and calculated total INP concentrations offline using the INP parameterizations from the Base simulation. Additional calculations excluding bacterial or dust INPs were also conducted to examine their contributions. Because the observations are based on measurements conducted at specific times and locations, whereas the model values represent monthly means over the grid cells crossed by the ship track in each month, this comparison includes uncertainty associated with differences in both temporal and spatial representativeness.*

The above content has been added to the manuscript at **lines 163–169**, and the results are shown in Figure S2.

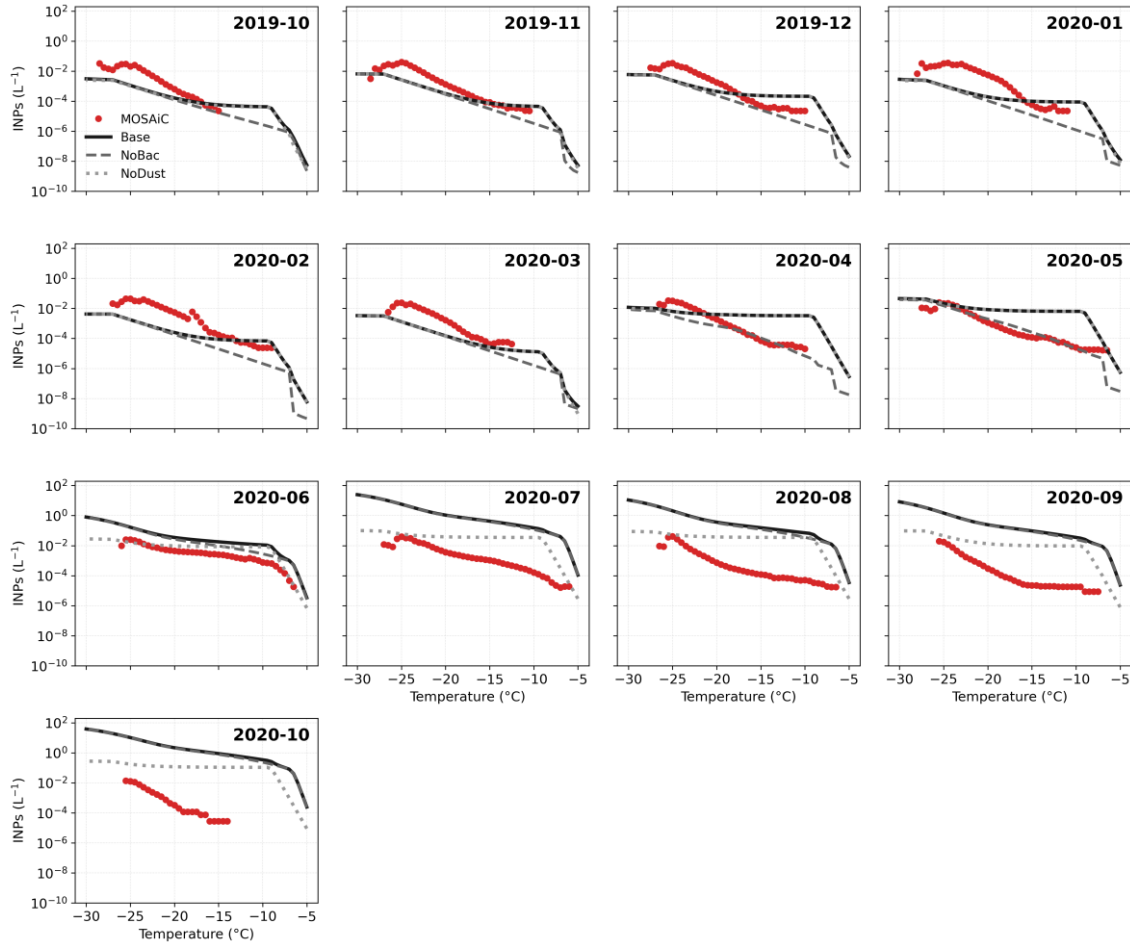


Figure S2. Temperature dependence of simulated and observed monthly mean INP number concentrations, corresponding to the observation periods and ship positions of the MOSAiC campaign. For each month, observations are shown as red dots, while the Base, NoBac (excluding bacteria), and NoDust (excluding dust) calculations are shown by the black solid, gray dashed, and gray dotted lines, respectively.

We have incorporated this comparison into Section 3.1 of the revised manuscript and have also revised the relevant descriptions in the Conclusions, as shown below.

***L199** The comparison with the INP number concentrations observed during the MOSAiC campaign shows that the model captures the observed temperature dependence of INP concentrations reasonably well and generally reproduces their overall concentration levels, particularly from October 2019 to June 2020 (Fig. S2). During this period, most simulated values are within two orders of magnitude of the observations, although larger discrepancies occur in April and May 2020 around -10°C , likely due to the high INA of bacteria at relatively high subzero temperatures in the model. The model tends to overestimate INP concentrations when the observations were made near Svalbard (from July to October 2020). As discussed above, the model overestimates dust concentrations around Svalbard, which may partly explain these discrepancies.*

L371 The model generally reproduces the observed magnitude and temperature dependence of INP concentrations at multiple Arctic sites (Conen et al., 2016; Mason et al., 2016; Tobo et al., 2019; Wex et al., 2019) and during the MOSAiC expedition (Creamean et al., 2022). Differences between simulated and observed INP concentrations are found under conditions strongly influenced by bacterial INPs and in the Svalbard region, where dust concentrations are overestimated in the model (Kawai et al., 2023; Matsui et al., 2024).

L136 Source attribution would be interesting to see here, what INPs in the model are dominant for each location? Similar to Kawai Fig. 1 e-h. It cannot be compared to observations but would be an interesting first-order estimate of what seems to be important for each location. Especially the non Arctic vs Arctic INPs would be interesting to see.

We thank the reviewer for this suggestion. We have conducted a source attribution analysis of INPs at each observation site, which yielded several insights. We have added Figure 2 and the following discussion to the manuscript.

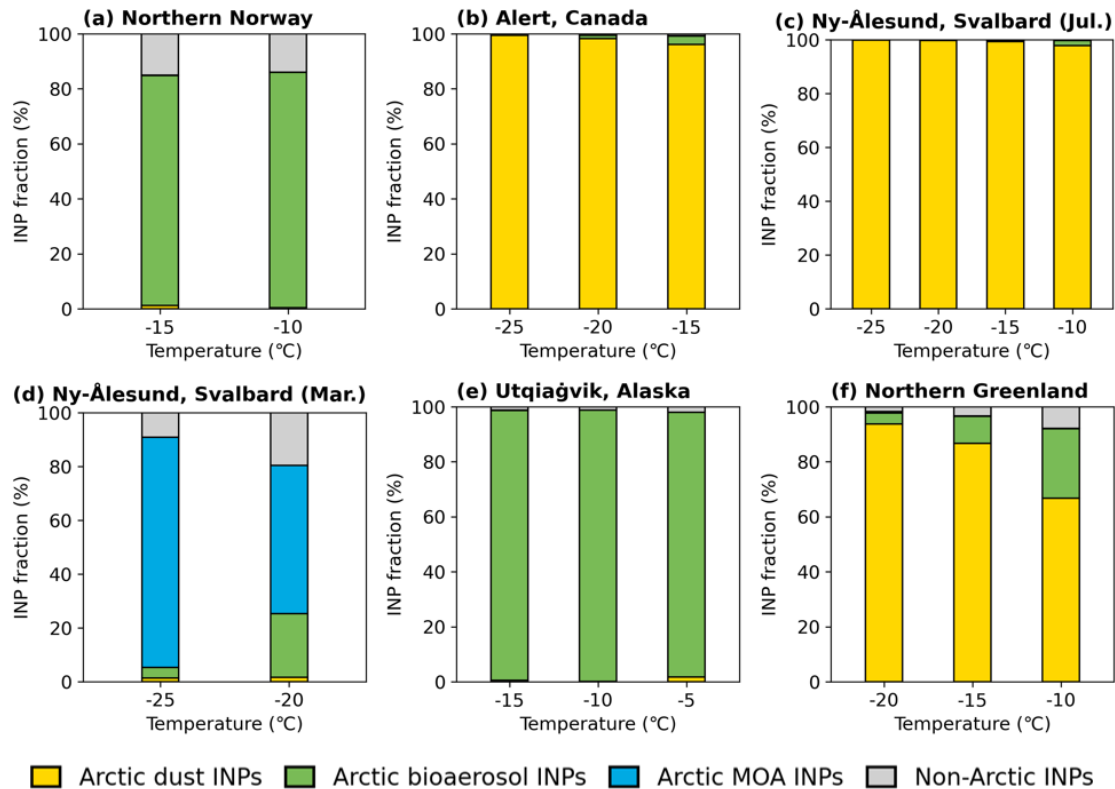


Figure 2. Fractions of Arctic dust INPs (yellow), Arctic bioaerosol INPs (green), Arctic MOA INPs (blue), and non-Arctic INPs (gray) in the total INP number concentrations simulated in the Base simulation at each observation site and temperature.

L190 The contributions of individual aerosol species vary with location, temperature, and season (Fig. 2). Arctic bioaerosols dominate total INPs at Northern Norway and Utqiagvik, whereas Arctic dust is the primary contributor at Alert and Northern Greenland. At Ny-Ålesund, Arctic dust contributes most in summer, while Arctic MOA dominates in spring. At Alert, Ny-Ålesund, and Northern Greenland, the contribution of Arctic bioaerosols generally increases with temperature within the observed temperature ranges. Because all of these observation sites are located at relatively low altitudes in the lower troposphere, contributions from non-Arctic sources are small.

L143 It would be useful to state when these measurements took place (season), to understand results for Norway and Alaska

We have added the following information to the caption of Figure 1.

Figure 1. Temperature dependence of INP number concentrations at various Arctic locations: (a) Northern Norway (July 2015), (b) Alert, Canada (from March 2014 to July 2015), (c) and (d) Ny-Ålesund, Svalbard (July 2016 and March 2017, respectively), (e) Utqiagvik, Alaska (Different months from June 2012 to June 2013), and (f) Northern Greenland (Different months in 2015 and 2013).

Detailed information on the observations is provided in the table below.

Table R1. Information of observations used for model evaluation in Figure 1.

Observational sites	Locations	Periods and temperatures
a. Northern Norway	Haldde observatory, 69.93° N, 22.81° E, 905 m a.s.l.	2015.7.2–2015.7.6 –15°C, –10°C
b. Alert, Canada	Dr. Neil Trivett Global Atmosphere Watch Observatory, 82.45° N, 62.51° W, 200 m a.s.l.	2014.3.29–2015.7.23 –25°C, –20°C, –15°C
c. and d. Ny-Ålesund, Svalbard	Zeppelin Observatory, 78.91° N, 11.88° W, 475 m a.s.l.	2016.7, 2017.3 ● –25°C, –20°C: Mar. and Jul. ● –15°C, –10°C: Jul.
e. Utqiagvik, Alaska	71.30 ° N, 156.77 ° W, 11 m a.s.l.	2012.6–2013.6 ● –15°C: Jan., Feb., Mar., May, Sep., Oct., Nov., Dec. ● –10°C: Jan.–Dec. ● –5°C: May, Aug., Oct.

f. Northern Greenland	Villum Research Station (VRS) 81.60° N, 16.67° W, 24 m a.s.l.	Different months in 2015 and 2013.12 ● −20°C: Jan., Jun., Nov., Dec. ● −15°C: Jan., Jun., Nov., Dec. ● −10°C: Jan., Apr., Jun., Jul., Oct., Nov., Dec.
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L144 What does the INP spectrum look like without dust? How much would one need to tune down the dust contribution to have comparable results to the observations? Would be useful to define a scaling factor.

We examined the INP concentrations from the Base simulation with dust INPs excluded at Ny-Ålesund, Svalbard (July) (Fig. R7). Dust dominates the simulated INPs at this site during this period (Fig. 2), and therefore excluding dust substantially reduces the INP concentrations.

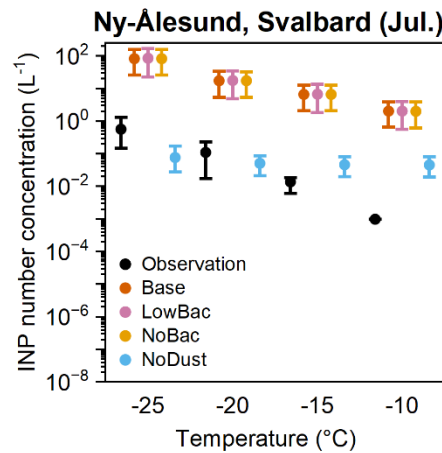


Figure R7. Temperature dependence of INP number concentrations at Ny-Ålesund, Svalbard (July 2016). The data points represent the averaged INP number concentrations. For the observations, the data points and error bars represent the mean values and the minimum–maximum ranges of the daily observed INP number concentrations, respectively. For the simulations, the data points and error bars represent the mean values and the interannual variability (minimum–maximum ranges) of INP number concentrations for the corresponding observation month(s) during 2010–2019, respectively. Observational data are shown in black. Model results for the Base, LowBac, NoBac, and NoDust cases are shown in red, pink, yellow, and blue, respectively.

For example, at −25°C, where the INP concentration is highest, Arctic dust accounts for nearly all of the simulated INPs. The Base simulation gives an INP concentration of 84 L^{−1}, compared with 0.57 L^{−1} in the observations, corresponding to an overestimation of about two orders of magnitude. A scaling factor of approximately 1/100 for the dust contribution would therefore bring the simulated value close to the observation at this temperature.

As described in our response to the comment on Section 3.1, our model tends to overestimate dust concentrations only around Svalbard (Matsui et al., 2024; Fig. S3), which likely contributes to the overestimation of INPs at Ny-Ålesund.

Figure 1 Caption Please see Technical Corrections for updates to the plot.

We have revised Figure 1 and its caption as suggested. Please refer to our response to the Technical Corrections.

“mean” Mean or geometric mean? Geometric mean would make a lot more sense for data that span orders of magnitude.

Here, "mean" refers to the arithmetic mean. We used the arithmetic mean because our purpose is to compare the temporally averaged INP concentrations between the different periods, rather than to characterize the frequency distribution or the typical magnitude of the concentrations.

“interannual variability” Why do only some have error bars? I do not believe Alaska for example has no interannual variability. Also, what is the reported error bar in the observations, most of these stations do not have several years of data? The uncertainty in INP concentration from observations should be reported consistently, why does Alert not have any uncertainty?

For the observations, the error bars represent the minimum–maximum ranges of the daily data within the observation period. For the offline calculations, they represent interannual variability for the corresponding observation month(s) during 2010–2019. No error bar is shown for Alert because only a single set of samples was available (Mason et al., 2016). Error bars are included for all offline calculations, although some are difficult to see because of their small ranges (e.g., the Utqiagvik results). We have revised Figure 1 to make the error bars more visible and updated the caption accordingly.

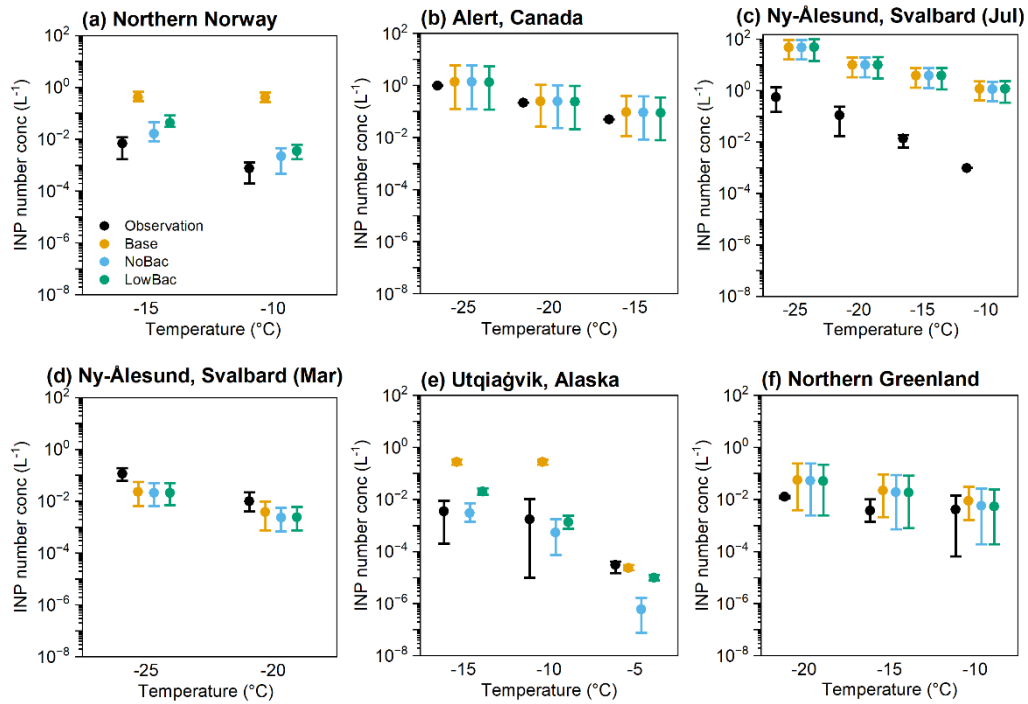


Figure 1. Temperature dependence of INP number concentrations at various Arctic locations: (a) Northern Norway (July 2015), (b) Alert, Canada (from March 2014 to July 2015), (c) and (d) Ny-Ålesund, Svalbard (July 2016 and March 2017, respectively), (e) Utqiagvik, Alaska (June 2012 to June 2013, with observation periods varying by temperature), and (f) Northern Greenland (2013 and 2015, with observation periods varying by temperature). For the observations, the data points and error bars represent the mean values and the minimum–maximum ranges of the daily observed INP number concentrations, respectively. For the simulations, the data points and error bars represent the mean values and the interannual variability (minimum–maximum ranges) of INP number concentrations for the corresponding observation month(s) during 2010–2019, respectively. Observational data are shown in black. Model results for the Base, NoBac, and LowBac cases are shown in yellow, blue, and green, respectively.

At Northern Norway and Utqiagvik, Arctic bioaerosols dominate the simulated INPs (Fig. 2). Their number concentrations show relatively small interannual variability during 2010–2019 (Table R2), resulting in small interannual variability in the simulated INP concentrations and therefore smaller error bars in Fig. 1.

Table R2. Simulated 10-year means, standard deviations, and coefficients of variation (CV) of annual Arctic dust, MOA, and bioaerosol concentrations at each observation site during 2010–2019.

	Arctic dust (ng m ⁻³)	Arctic MOA (ng m ⁻³)	Arctic bioaerosols (m ⁻³)
Northern Norway	23.3 ± 18.5 (CV = 79.5%)	8.71 ± 4.89 (CV = 56.1%)	2.01e+04 ± 4.27e+03 (CV = 21.2%)
Alert, Canada	553 ± 980 (CV = 177.1%)	1.05 ± 0.461 (CV = 44.0%)	259 ± 150 (CV = 58.1%)
Ny-Ålesund, Svalbard	3.22e+04 ± 1.76e+04 (CV = 54.6%)	10.8 ± 9.31 (CV = 86.2%)	2.08e+03 ± 927 (CV = 44.6%)
Utqiagvik,	6.68 ± 7.44	6.17 ± 1.61	1.33e+04 ± 1.82e+03

Alaska	(CV = 111.5%)	(CV = 26.0%)	(CV = 13.7%)
Northern Greenland	99.7 ± 129 (CV = 129.2%)	1.47 ± 0.491 (CV = 33.3%)	123 ± 65.7 (CV = 53.5%)

L162 Perhaps for some people these values mean something, for me it is hard to put this in perspective. Could these values be compared with global means perhaps? Or compared to other studies (see L178 for MOA)

As suggested by the reviewer, we compared our estimates with values reported in previous studies where available. The following discussion has been added to the manuscript.

***L210** Arctic dust emissions are comparable to those reported by Groot Zwaafink et al. (2016) and in our previous study (Kawai et al., 2023). For Arctic MOA emissions, our estimate over 66–90°N (0.15 Tg y⁻¹) is approximately 2.6 times the value reported by Leon-Marcos et al. (2026) (0.057 Tg y⁻¹). This difference may partly be related to our use of average POC values at high latitudes where MODIS POC data are unavailable (Section 2.2).*

L163 When referring to all these seas, perhaps the regions could be specified in S1 to make sure people can identify which regions are where.

We have revised Figure S1 as suggested by adding the relevant information.

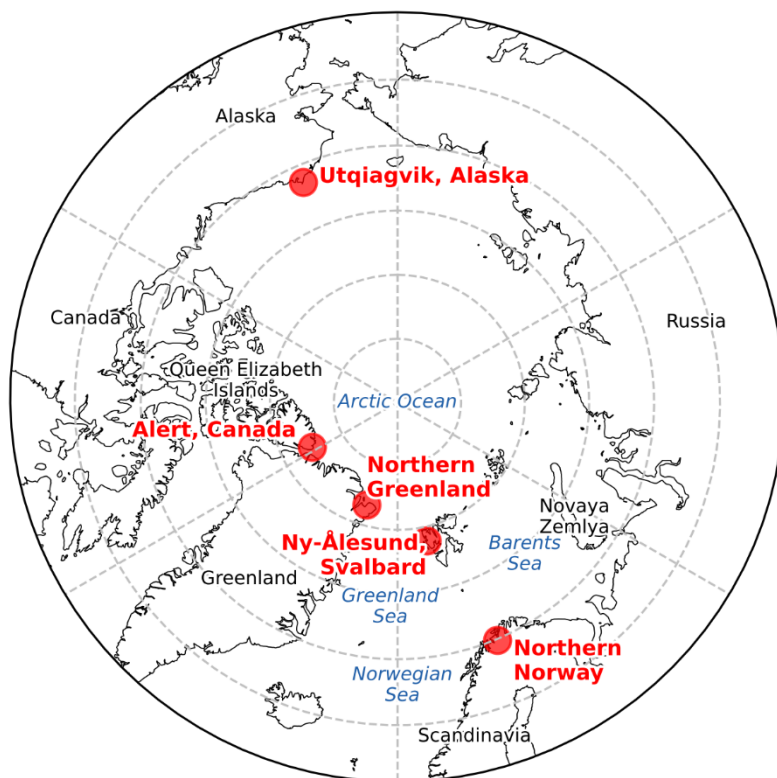


Figure S1: Locations of observational sites, including Northern Norway (69.93°N, 22.81°E, 905 m a.s.l.), Alert, Canada (82.45°N, 62.51°W, 200 m a.s.l.), Ny-Ålesund, Svalbard (78.91°N, 11.88°W, 475 m a.s.l.), Utqiagvik, Alaska (71.30°N, 156.77°W, 11 m a.s.l.), and Northern Greenland (81.60°N, 16.67°W, 24 m a.s.l.). Sites are marked by red circles and labelled in red text. Land regions and islands referred to in the manuscript are labelled in black, and ocean and sea names in blue.

L167 “Aerosols in these regions consequently act as INPs and contribute to ice crystal formation in clouds.” is unnecessary here.

We have deleted this sentence as suggested.

L168 Again, for the vertically mean (would geometric mean make more sense?) and INP concentration could the authors put these values in perspective?

We use the arithmetic spatiotemporal mean for the INP concentrations. Please also see our response to the comment on the Figure 1 caption.

Our values are not directly comparable to those reported in previous studies because most reported INP concentrations are defined at fixed temperatures, whereas our values represent in-cloud INP concentrations calculated using the ambient temperature at each model timestep.

Fig 2 caption How is the mean calculated? Day-count? Monthly means? Again arithmetic mean or geometric?

The “mean” here refers to the arithmetic mean of the monthly output data. Each month is weighted equally, and no day-count weighting is applied. We have added the following statement to Section 2.4:

***L138** The first year was treated as the model spin-up, and the monthly mean outputs from the subsequent 40 years (from 1981 to 2020) were used for analysis.*

L178 “Notably, Arctic MOA is present year-round” Can the authors elaborate on why this is the case? Leon-Marcos et al. 2025 (<https://acp.copernicus.org/articles/26/1109/2026/>) modelled PMOA in the Arctic and find that the PMOA peaks around May-September. This would also be a good paper to compare the total MOA emissions with. I assume the seasonality shown here is due to the seasonality of the TOC for the MOA parameterisation used by Wilson et al. 2015? Is the MOA during winter mostly located at lower latitudes, close to the cut off at 60°N?

Thank you for suggesting this relevant study. We compared our results with those of Leon-Marcos et al. (2026). Over the same domain (66–90°N), our simulated MOA emission is 0.15 Tg yr⁻¹, approximately 2.6 times the estimate of 0.057 Tg yr⁻¹ reported by Leon-Marcos et al. (2026). This difference may partly reflect differences in the treatment of POC and in the MOA emission parameterizations between the two models.

Leon-Marcos et al. (2026) showed a pronounced seasonal cycle in PMOA emissions, with a maximum from May to September. In our model, MOA emissions are controlled mainly by sea-spray emissions over ice-free ocean rather than by seasonal changes in ocean biological productivity. Because our Arctic domain extends to 60°N, MOA emissions occur throughout the year, but their source regions vary seasonally. In summer and fall, emissions are concentrated mainly in regions of sea-ice retreat (Fig. R8), whereas in winter they originate mainly from perennially ice-free regions such as the Greenland Sea and southern Norwegian Sea near 60°N (Fig. S8).

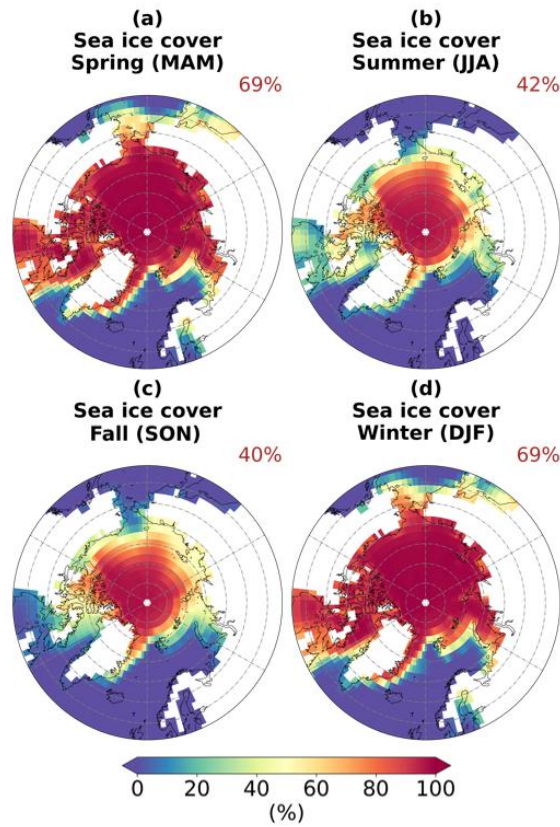


Figure R8. Spatial distributions of sea ice cover in the Arctic during 1981–2020 for (a) spring (MAM), (b) summer (JJA), (c) fall (SON), and (d) winter (DJF). The numbers in the upper right corner of each panel indicate the 40-year mean averaged over the Arctic.

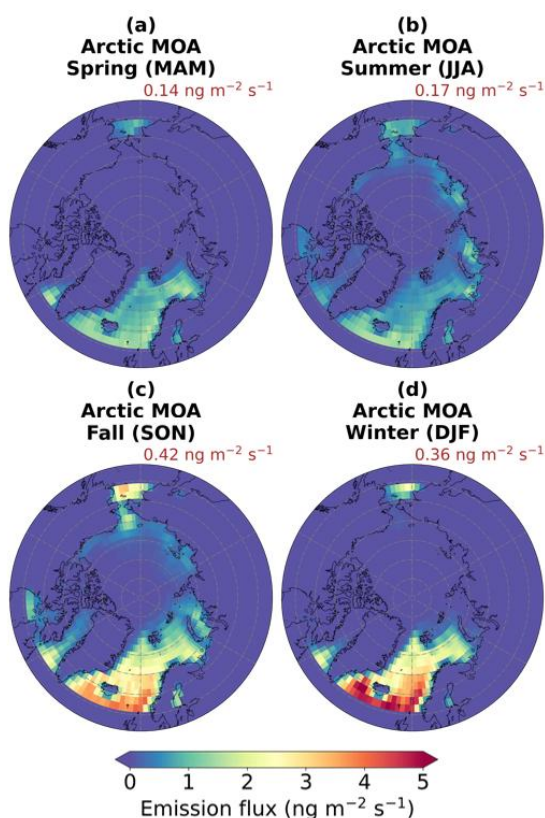


Figure S8. Spatial distributions of MOA emissions in the Arctic during 1981–2020 for (a) spring (MAM), (b) summer (JJA), (c) fall (SON), and (d) winter (DJF). The numbers in the upper right corner of each panel indicate the 40-year mean averaged over the Arctic.

In response to this comment, we have added the following statements to the manuscript:

L211 For Arctic MOA emissions, our estimate over 66–90°N (0.15 Tg y^{-1}) is approximately 2.6 times the value reported by Leon-Marcos et al. (2026) (0.057 Tg y^{-1}). This difference may partly be related to our use of average POC values at high latitudes where MODIS POC data are unavailable (Section 2.2).

L238 MOA emissions in summer and fall originate predominantly from regions of sea ice retreat, whereas winter emissions originate mainly from perennially ice-free regions (Fig. S8).

L188 Yes, but this is not seen in the figures? → see SC2.

Please refer to our response to SC2.

L196-199 While not untrue, this is nothing new. There is no importance to highlight here as these are not evaluated against observations. Rather, I think the important outcome of

this part is that we have a first-order estimate of seasonal, spatial, and vertical distribution of INPs in the Arctic. Furthermore, “associated INPs”, INP parameterisations perhaps? or what are the authors wanting to convey here?

We agree with the reviewer that the main finding of this part is the first-order estimate of the seasonal, spatial, and vertical distributions of Arctic INPs. We have therefore revised the corresponding text accordingly. Here, "associated INPs" refers to the calculated INP number concentrations.

L255 These results provide a first-order estimate of the three-dimensional distribution and seasonal variation of INPs within clouds in the Arctic, which remain poorly constrained by observations. The distinct spatial distributions and seasonal variations of INPs from the three species highlight the importance of explicitly representing Arctic dust, Arctic MOA, Arctic bioaerosols, and their INPs in models.

Section 3.3

I find Figure 4 quite peculiar. So, the Arctic INPs seem to dominate over the areas of local emission in the Arctic (comparing Fig. 2 and Fig. 4). Dust across the Arctic islands and bio across the forests and MOA also mostly where it is emitted. But the local sources in the Arctic seem to only contribute to ~50% of the INPs at 90°N. Does this mean that the local sources are not transported very far? This could be quite interesting to add some discussion on, as INP measurements during the MOSAiC campaign (Creamean et al. 2022 <https://www.nature.com/articles/s41467-022-31182-x>) see a strong seasonal cycle in local vs long-range transported INPs.

We thank the reviewer for this insightful observation.

Our results show that, during 1981–2020, locally emitted dust, bioaerosols, and MOA in the lower Arctic atmosphere are largely confined to their source regions (Fig. 3), and that at 90°N these local sources contribute only ~50% of the total INP concentration (Fig. 5), with the remainder supplied by long-range transport from lower latitudes. This reflects efficient dry deposition and wet scavenging during transport across the marginal ice zone, consistent with previous studies of Arctic aerosol transport (e.g., Stohl, 2006; Willis et al., 2018).

Figure R9 shows the seasonal spatial distributions of the contribution of Arctic INPs to the total INPs in the Arctic lower troposphere. In summer and fall, Arctic INPs dominate over most of the Arctic, contributing 97% and 84% of total INPs, respectively. Even over the central Arctic Ocean at 90°N, their contribution is approximately 80%, mainly from Arctic dust emitted from islands in the central Arctic Ocean and Arctic bioaerosols from land regions (Figs. 5 and 6).

In spring and winter, Arctic INPs contribute mainly over oceanic regions (Fig. R9), where Arctic MOA from oceanic sources dominates (Figs. 5 and 6). In contrast, INPs over land regions are dominated by aerosols transported from outside the Arctic (Fig. R2), consistent with Creamean et al. (2022). At 90°N, Arctic INPs contribute approximately 30% in spring and 50% in winter.

These seasonal differences result in an annual mean contribution of ~50% from Arctic INPs to total INPs at 90°N. Overall, the contribution of Arctic INPs to total INPs shows a pronounced seasonal and spatial variation.

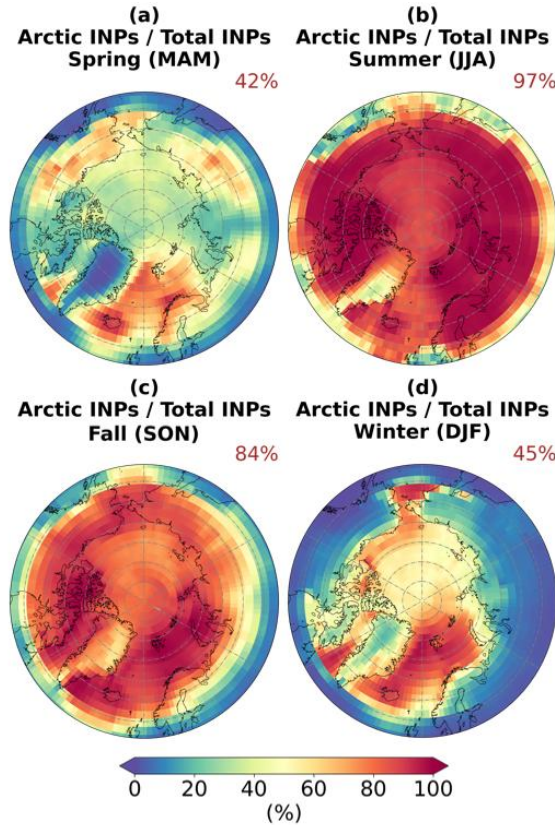


Figure R9. Spatial distributions of the contribution of Arctic INPs to total INPs in the Arctic lower troposphere (> 730 hPa) during 1981–2020 for (a) spring (MAM), (b) summer (JJA), (c) fall (SON), and (d) winter (DJF). The numbers in the upper right corner of each panel indicate the 40-year mean averaged over the Arctic lower troposphere.

We have added this figure to the Supplementary Information as suggested and incorporated the following description into the manuscript.

L277-286 Arctic aerosols contain a substantial fraction of coarse particles and are therefore efficiently removed by dry and wet deposition, limiting their long-range transport. Consequently, the contribution of Arctic INPs decreases toward the central Arctic, reaching approximately 50% at 90°N. Seasonally, Arctic INPs dominate total INPs in summer and fall in the Arctic lower tropospheric clouds (Fig. 6d), with mean contributions of 97% and 84%, respectively (Fig. S10). In summer, their contributions exceed 80% across almost the entire Arctic. In spring

and winter, Arctic INPs contribute 42% and 45%, respectively, with relatively large contributions over perennially ice-free ocean regions such as the Greenland Sea and Norwegian Sea, where Arctic MOA is a major source (Fig. S4). In contrast, non-Arctic INPs dominate over Greenland and continental regions during these seasons. Overall, INPs in the Arctic lower tropospheric clouds are influenced by both Arctic and non-Arctic sources throughout the year, with their relative contributions varying seasonally with changes in snow and sea-ice cover.

L203 This is annual means? Would be also interesting to see this split into seasonal contributions, especially as the bioaerosols are defined by this cycle. Furthermore, could the authors partition the contributions from the non-Arctic species as well? It would be interesting to see for example how much of the dust INPs are from local sources and the same for the other 2 INP types

Yes, this is the annual mean of the 40-year period. For seasonal contributions, we have added a relevant figure to the Supplementary Information and incorporated a relevant discussion into the sections discussing seasonal variation, as shown below.

L268 Arctic dust INPs dominate in summer (Fig. 6), contributing 77% of the total INPs in lower tropospheric clouds (Fig. S9). Arctic MOA INPs contribute most in winter, reaching 35% of total INPs in the lower troposphere. Arctic bioaerosol INPs contribute substantially from spring to fall in regions with temperatures around -10°C , with their contribution in lower tropospheric clouds peaking at 37% in fall.

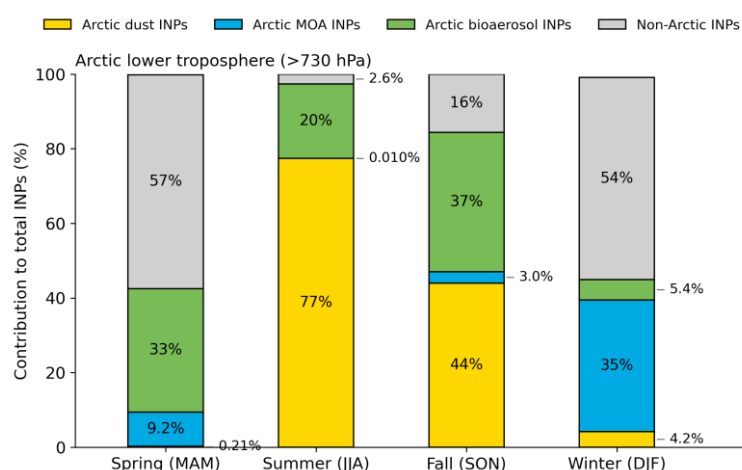


Figure S9. Seasonal contributions to total INPs in Arctic lower-tropospheric clouds (> 730 hPa). The numbers above the bars indicate the 40-year mean averaged over the Arctic lower troposphere.

Regarding the seasonal variation and vertical distribution of the species-specific contributions of non-Arctic INPs, please refer to our response to SC3. In the lower

troposphere, non-Arctic dust, non-Arctic MOA, and non-Arctic bioaerosols contribute 6.2%, 1.9%, and 19% to total INPs, respectively. Among the non-Arctic components, bioaerosols are the largest contributor in the lower troposphere, whereas dust is the dominant contributor in the upper troposphere.

Fig. 5 → SC2

Please see our response to the SC2.

L224 This has been done before with other models/methods. Could the authors give some comparisons to previous studies? For example Rantanen et al. 2022 <https://www.nature.com/articles/s43247-022-00498-3>, would be good to compare the results presented here such that they show a similar trend to the observational datasets.

In our study, the simulation shows a warming rate of approximately $0.54^{\circ}\text{C decade}^{-1}$. This is consistent in magnitude with the 1979–2021 warming rate of $0.73^{\circ}\text{C decade}^{-1}$ reported by Rantanen et al. (2022), who used the average of four observational datasets (GISTEMP, Berkeley Earth, HadCRUT5, and ERA5) and defined the Arctic as the region poleward of the Arctic Circle ($> 66.5^{\circ}\text{N}$). In our study, the domain is defined as $60\text{--}90^{\circ}\text{N}$, and the slightly lower rate is consistent with the broader domain adopted here, which includes mid-to-high-latitude land and ocean areas that warm less rapidly than the inner Arctic. Rantanen et al. (2022) likewise show that the Arctic amplification ratio increases as the regional definition is narrowed toward the pole (their Fig. 2). Spatially, our simulation produces the strongest warming over islands and coastal areas of the central Arctic Ocean (Fig. 7), in agreement with Rantanen et al. (2022), who reported regional warming rates up to seven times the global mean over the Barents Sea near Novaya Zemlya.

We have added a quantitative comparison to the revised manuscript.

L291 *The annual mean surface air temperature in the Arctic increases by 1.6°C , from -9.5°C during 1981–1990 to -7.8°C during 2011–2020 (Figs. S11 and S12), corresponding to a warming rate of approximately $+0.54^{\circ}\text{C decade}^{-1}$. This is comparable in magnitude to the 1979–2021 warming rate of $+0.73^{\circ}\text{C decade}^{-1}$ reported by Rantanen et al. (2022) for the region north of 66.5°N . The slightly lower rate in our study is consistent with our broader Arctic domain ($60\text{--}90^{\circ}\text{N}$), which includes lower-latitude regions that warm less rapidly than the inner Arctic.*

L303 *The pronounced warming and sea ice retreat simulated over the Barents Sea are consistent with the analyses of Rantanen et al. (2022) and Stroeve and Notz (2018). These results illustrate the close relationship between Arctic warming and reductions in snow and sea ice cover.*

L230-231 Same for this line, make sure to include some appropriate references

We have added comparisons to the manuscript, as shown below.

***L295** Snow and sea ice cover in the Arctic decrease from 68% to 66% and from 59% to 52%, respectively, between the 1981–1990 and 2011–2020 averages. The corresponding decline rates are approximately –1% per decade for snow cover and –4% per decade for sea-ice cover. These rates are consistent with the sea ice decline rate for 1979–2020 reported by the NSIDC (Perovich et al., 2021) and the snow cover decline rate reported in the Arctic Report Card 2020 (Mudryk et al., 2020).*

L254 It looks like maybe the reductions in Arctic dust and MOA are also connected to positive trends in sea ice/snow cover? Why are these trends sporadically seen?

Bioaerosol emissions show a good correspondence with snow cover fraction. Decreases in Arctic dust and MOA emissions in some regions are also consistent with local increases in snow and sea ice cover, respectively. However, the spatial patterns do not correspond exactly because dust and MOA emissions are also strongly influenced by wind speed. The causes of these localized positive trends in snow and sea ice cover are beyond the scope of this study, but they may reflect regional and internal climate variability.

L258 Also refer to Fig. 7 g-i here

We have added figure references as suggested.

***L336** While Arctic aerosol emissions increase over the four decades, concentrations of Arctic INPs in clouds decline (Figs. 8g–i and S6g–i) because the temperature effect outweighs the emission effect.*

L265-270 Would be good to mention the reason here (the increase in temperature) to explain the results better. Ok, it is mentioned in L284 but again with the “decreasing INA” explanation. Unless there is a good reason to rename the temperature effect please stick with this established key phrase. → SC1

For the Arctic mean and across most Arctic regions, the decreasing trend in total INPs is primarily driven by the temperature effect, whereas in some regions, the emission effect is dominant. We have added the following sentences for clarity.

***L346** The decrease of total INPs in the Arctic lower tropospheric clouds is broadly*

simulated over islands in the central Arctic Ocean, coastal waters, and continents (Fig. 9b), mainly due to the temperature effect. In contrast, total INPs increase in some regions where aerosol emissions increase substantially, reflecting the stronger emission effect.

We have also revised the wording at L284 of the original manuscript.

***L361** Changes in Arctic INPs in clouds are controlled by the balance between the increase in INPs caused by increasing emissions (emission effect) and the decrease in INPs caused by lower INA at higher temperatures (temperature effect) (Matsui et al., 2024).*

L268 How does a strong aerosol emission influence the activation of INPs? While there are more (number) this should not have any impact on the INP concentration if it is too warm. Are there some aerosol dynamics in play that leads to larger sizes which more readily freeze at warmer temperatures? Please expand on this

This does not refer to a change in aerosol dynamics or ice nucleating ability. In these regions, the increase in INPs caused by enhanced aerosol emissions is larger than the decrease in INPs associated with higher ambient temperatures. Therefore, the emission effect outweighs the temperature effect, resulting in a net increase in INP concentrations. We have added the following sentence to the manuscript.

***L349** In other words, in these regions, the increase in INPs caused by enhanced aerosol emissions is larger than the decrease in INPs associated with higher ambient temperatures.*

L307 How does the contribution of Arctic INPs increase with a decrease in bioaerosols? Perhaps I'm missing something?

When the parameterization is switched from BASE to LowBac, both Arctic and non-Arctic bioaerosol INPs decrease. Because the decrease is larger for non-Arctic bioaerosol INPs, the relative contribution of Arctic INPs increases.

Conclusions

Overall: There are no references in the conclusion, try to connect the results to other studies of Arctic INPs from the observational and modelling communities as well as comparisons to global studies to put the work in perspective

We have added citations throughout the Conclusions section and incorporated additional content, as shown below.

L371 *The model generally reproduces the observed magnitude and temperature dependence of INP concentrations at multiple Arctic sites (Conen et al., 2016; Mason et al., 2016; Tobo et al., 2019; Wex et al., 2019) and during the MOSAiC expedition (Creamean et al., 2022). Differences between simulated and observed INP concentrations are found under conditions strongly influenced by bacterial INPs and in the Svalbard region, where dust concentrations are overestimated in the model (Kawai et al., 2023; Matsui et al., 2024).*

L379 *Arctic INPs dominate total INPs in the Arctic lower troposphere in summer and fall, while non-Arctic INPs play a more important role in spring and winter. This seasonal pattern is consistent with the seasonal trends observed during the MOSAiC campaign (Creamean et al., 2022).*

L402 *Reducing uncertainties in the INP parameterizations of bioaerosols is important given the good agreement between observations and the Base simulation on a global scale (Kawai et al., 2026), as well as recent observational studies that have emphasized the significance of bioaerosols for Arctic INPs (Kawana et al., 2024; Pereira Freitas et al., 2023; Šantl-Temkiv et al., 2019).*

L330 Specify the model

We specified the model CAM-ATRAS

L370 *In this study, we simulated interannual changes in aerosols and ice nucleation in mixed-phase clouds in the Arctic during 1981–2020 with three aerosol species—dust, MOA, and bioaerosols—using the global climate-aerosol model CAM-ATRAS.*

Fig. 9 I am not a fan of introducing figures in the conclusions but as this seems to be an overview figure, alright. Could the authors at least state something like “Overview of results” or similar in the caption?

We have removed Figure 9 and do not refer to any figures in the Conclusions section.

L363 I think this a bit of an overstatement as the authors are only exploring different parameterisations for bacteria. What about differences for dust? And MOA? → SC4

We thank the reviewer for pointing out this issue. The present study does not aim to systematically compare different INP parameterizations, but rather to provide a first-order estimate of three species of Arctic INPs in clouds, quantify their contributions and seasonal variations, and characterize changes in INPs under Arctic warming. We therefore agree that placing excessive emphasis on the importance of “selecting appropriate INP parameterizations” is not appropriate in the context of this study. We have revised or removed statements that could blur this focus or overstate our findings, and have revised this sentence as follows.

***L401** Overall, this study provides a first-order estimate of Arctic INPs in clouds from dust, MOA, and bioaerosols, illustrating their relative contributions and seasonal variations.*

Data availability

These days data, when possible, should be made available. I can understand if the data is rather large but could perhaps a subset be made public, perhaps the model data shown in Fig. 1 which could be useful for future studies to compare with?

For the review process, we uploaded the data used to generate the figures at the link below.

<https://nuss.nagoya-u.ac.jp/s/4Xe4JgWoCr85rDa>

If the manuscript is accepted, these data will be archived in a public repository such as Zenodo, and the corresponding link will be added to the Data Availability section.

Technical Corrections

Fig 1 Please make the markers larger and add the error bar caps for better visibility. Add a legend for the colours in at least one of the plots. Make the marker for observations different to the marker for the model for better clarity (black/white print outs for example).

Additionally, these colours are not colourblind friendly, please make sure they are:

<https://www.color-blindness.com/coblis-color-blindness-simulator/>

We have revised Figure 1 as suggested.

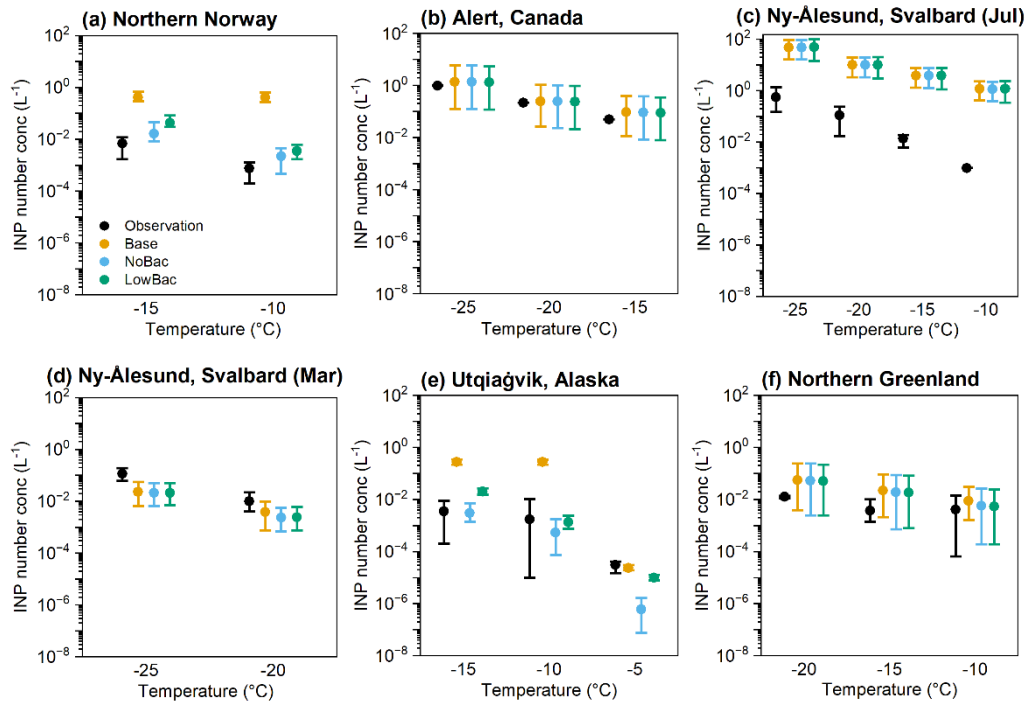


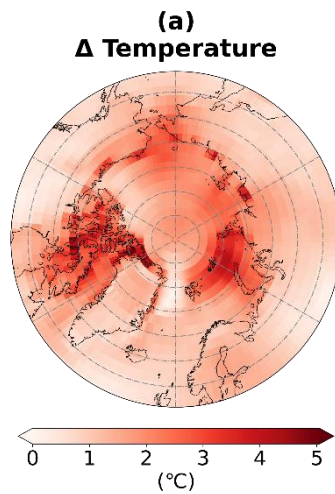
Figure 1. Temperature dependence of INP number concentrations at various Arctic locations: (a) Northern Norway (July 2015), (b) Alert, Canada (from March 2014 to July 2015), (c) and (d) Ny-Ålesund, Svalbard (July 2016 and March 2017, respectively), (e) Utqiagvik, Alaska (June 2012 to June 2013, with observation periods varying by temperature), and (f) Northern Greenland (2013 and 2015, with observation periods varying by temperature). For the observations, the data points and error bars represent the mean values and the minimum–maximum ranges of the daily observed INP number concentrations, respectively. For the simulations, the data points and error bars represent the mean values and the interannual variability (minimum–maximum ranges) of INP number concentrations for the corresponding observation month(s) during 2010–2019, respectively. Observational data are shown in black. Model results for the Base, NoBac, and LowBac cases are shown in yellow, blue, and green, respectively.

Fig 3 Use only one y-label for the row, this would save space. For d–f the same colourbar could be used to save the reader having to identify this themselves.

We considered using a single colorbar for panels d–f, as suggested. However, because the colorbars for panels a–c are set independently, using a common colorbar only for panels d–f would result in an inconsistent colorbar format across the figure. We would therefore prefer to retain the original colorbar configuration.

Fig 6 a) Make the temperature colourbar from 0°C to +5°C perhaps? Nuances could be more easily seen

We adjusted the temperature colorbar range as suggested. To further improve the visibility of the temperature variations, we also changed the colormap. The revised panel (Figure 7a) is shown below.



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