

Response to Anonymous Referee #2

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.

Major comments:

- More explanation on the methodology is needed: how are the INP exactly calculated? It states in the study that it is calculated instantaneous based on T and aerosol conc. and somewhere else that the calculation happens offline. Does that mean it is calculated on the 30 min (timestep of the model) output values for T and aerosol conc.? Is that output saved on this high time resolution? What information is used for the aerosol size, aerosol area, aerosol mass, aerosol volume (depending on the freezing parameterization)?

We use both online and offline calculations in this study. The offline calculations described in Section 2.5 of the manuscript were performed to compare the simulation results with observational data (Section 3.1). This analysis uses the simulated monthly mean aerosol concentrations at the observation sites to calculate INP number concentrations at the observed temperatures, using different INP parameterizations. Offline calculations are used only in Section 3.1, and all other analyses in the manuscript are based on the results of the online calculation. In the online calculations, 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 . In both the offline and online calculations, we used the same INP parameterizations (Table 1).

To clarify the INP calculation methods, we have added a table to the manuscript and revised the description as follows.

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) LowBac: Hummel et al. (2018)
	Fungal spores	Offline (Hoose et al., 2010)	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)

***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. The calculation includes dust, MOA, bioaerosols, and black carbon. Although black carbon INPs are calculated in the model and included in the total INPs, they are not specifically investigated in this study because their contribution is negligible. As outlined below, species-specific INP parameterizations are used to represent the temperature dependence of INA (Kawai et al., 2026).*

We have also added information on the particle size distributions of the relevant aerosol species in Section 2.2. The revised text is as follows:

***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).*

- The aerosol setup of CAM-ATRAS misses some information that makes it hard to understand the study setup. Can you please spell out all 11 aerosol species used in the model (dust, sea salt, MOA, pollen, bacteria, fungal spores, anthropogenic burning (=BC?), biomass burning (=BC?) are mentioned but that is not 11 species all together)? And then how many tracers does the model use in total - the 11 species + extra tracers (4?) for the distinction between Arctic/non-Arctic aerosols?

The 11 aerosol species represented in our model are (1) sulfate, (2) nitrate, (3) ammonium, (4) black carbon, (5) sea salt, (6) organic aerosol, (7) dust, (8) marine organic aerosols (MOA), (9) pollen, (10) bacteria, and (11) fungal spores. Pollen, bacteria, and fungal spores are collectively considered as bioaerosols. We used two separate tracers for dust, MOA, and bioaerosols to distinguish between Arctic and non-Arctic aerosols.

We have added the following description to the manuscript to address this comment:

***L78** CAM-ATRAS simulates 11 aerosol species, including sulfate, nitrate, ammonium, black carbon (anthropogenic burning and biomass burning), sea salt, organic aerosol, dust, MOA, pollen, bacteria, and fungal spores, with pollen, bacteria, and fungal spores collectively considered as bioaerosols.*

***L90** For dust, MOA, and bioaerosols, we use 2 separate tracers to distinguish between Arctic and non-Arctic aerosols.*

- I find the formulation of one of the major hypothesis (INA is reduced in future at ambient temperature) a bit confusing and would rewrite it. INA is a function of temperature and at the same temperature the INA value of one species is the same (all simulated decades). What is changing is the ambient temperature and that the INP efficiency is lower at warmer temperature. I would phrase this as an ambient temperature effect rather than a decrease in 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.*

- The Arctic INPs are calculated based on different parameterization schemes as the non-Arctic INPs. That makes sense, but given that you yourself show the high sensitivity of the results on the freezing parameterization scheme did you make a sensitivity test (this could be for a shorter time span, e.g. one year) how the result looks like if the same schemes are used? For example how does the ratio of Arctic dust INP/dust INP change if for both sources the same freezing parameterization scheme is used?

Our previous study (Kawai et al., 2023) examined the differences between two dust INP parameterization schemes, DeMott et al. (2015) (BASE simulation) and Tobo et al. (2019) (HIGH

simulation). In the Arctic lower troposphere (> 700 hPa) during summer and fall, Arctic dust INPs contribute approximately 100% of the total dust INPs in the HIGH simulation, compared with approximately 60% in the BASE simulation (Fig. R1). The vertically integrated number concentration of Arctic dust INPs in the HIGH simulation ($1,301 \text{ m}^{-2}$) is 186 times that in the BASE simulation (7.0 m^{-2}) (Fig. R2). Since this has already been examined in Kawai et al. (2023), we do not discuss it further in this study.

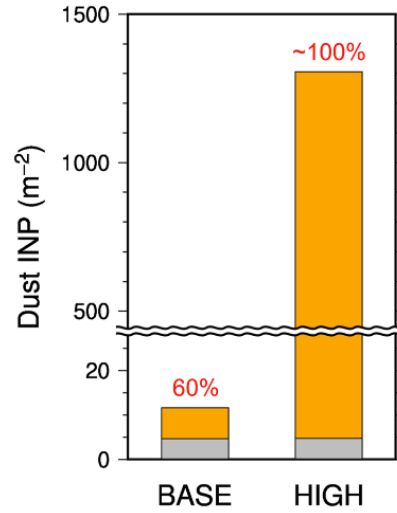


Figure R1. Figure 3a from Kawai et al. (2023). Vertically integrated number concentrations of Arctic dust INPs (orange) and other dust INPs (gray) in the lower troposphere (>700 hPa) averaged over the Arctic ($>60^\circ\text{N}$) during the summer and fall (June–November) of 2010–2019 in the BASE and HIGH simulations. The percentages above the bars represent the contributions of Arctic dust INPs to the vertically integrated number concentrations of total (Arctic + other) dust INPs.

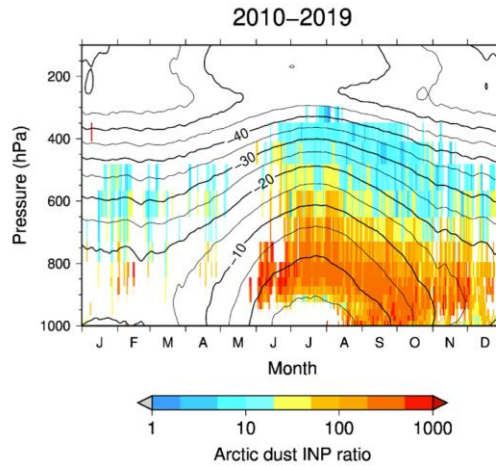


Figure R2. Figure S7 from Kawai et al. (2023). Time-height distribution of ratio of the number concentrations of Arctic dust INPs ($>0.01 \text{ m}^{-3}$) averaged in the Arctic ($>60^\circ\text{N}$) for the years 2010–2019 in the HIGH simulation to those in the BASE simulation. The contour lines represent isotherms in $^\circ\text{C}$ at 5°C intervals.

- Related to the point before: it would be great if you could add an overview plot of all INA(T) parameterizations for one example aerosol (=size, mass, area, volume).

Figure 1 of Kawai et al. (2026) provides an overview of the ice nucleating abilities of the aerosol species considered in this study (Fig. R3). Since this figure has already been presented in Kawai et al. (2026), we have not reproduced it in this manuscript. For a more detailed description of the INP parameterizations, please see our response to the first major comment and Figure R3. We have added this content to the manuscript at **lines 115-121**.

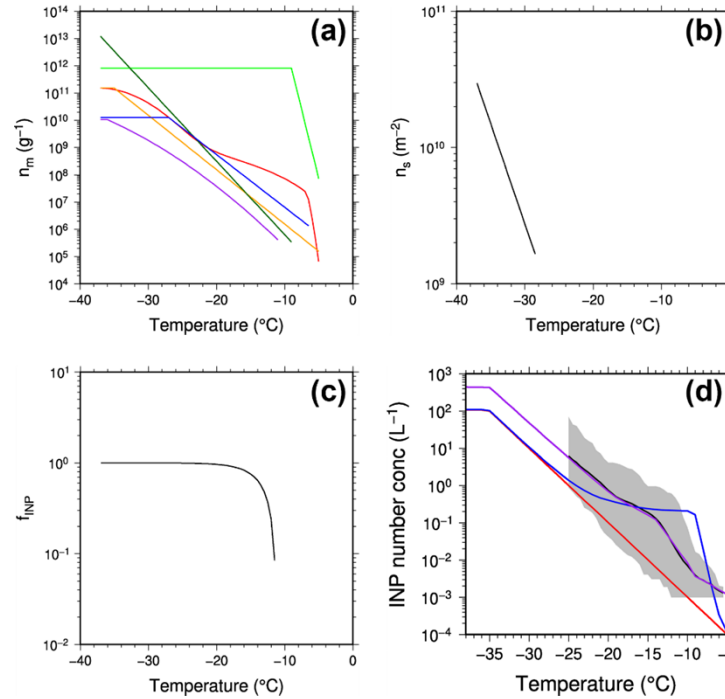


Figure R3. Figure 1 from Kawai et al. (in review) Ice nucleating abilities of aerosol species and types acting as INPs in this study. (a) The red, orange, light green, green, blue, and purple lines represent the ice nucleation active site density per unit mass (n_m) of Arctic dust, non-Arctic dust, bacteria, 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.

- Fig. 1: I guess it is limited by the temperature at which INP were observed (INP observations were available for all locations for the temperature plotted here?) what can be plotted here. However, a comparison can look very different at warm vs. cold temperatures.

We agree with the reviewer that the temperature range available for comparison is constrained by the temperatures at which INPs were observed. Specifically, observations at Northern Norway range from -15°C to -7°C (Conen et al., 2016); at Alert, Canada, observations include -25°C , -20°C , and -15°C (Mason et al., 2016); at Ny-Ålesund, Svalbard, observations range from -25°C to -15.5°C in July 2016 and from -25°C to -9.5°C in March 2017 (Tobo et al., 2019); at Utqiagvik, Alaska, observation temperatures range from -20°C to -5°C , varying by month; and at Northern Greenland, observation temperatures range from -21°C to -6°C , also varying by month (Wex et al., 2019). We have selected a subset of these observation temperatures and the corresponding observation periods for comparison.

- Fig. 2: This figure could be biased by the choice of the height (here lower troposphere) since T is coupled to that. Is it vertically integrated for all pressure levels >730 hPa right now? How does the result differ for a range of different heights or more interestingly for different temperature (but to show that exocitely instantaneous temperature binned output would be needed)?

Figure 2 presents the vertically weighted mean over all levels with pressure > 730 hPa, corresponding to model layers 22–30. Since mixed-phase clouds are prevalent in the Arctic lower troposphere, we analyze the main distribution patterns of Arctic INPs by focusing on their spatial distribution in the lower troposphere.

To investigate the sensitivity of the results to the vertical range, we calculated vertically weighted means over pressure levels > 652 hPa (Figs. R4a–c), corresponding to model layers 21–30, and > 796 hPa (Figs. R4d–f), corresponding to model layers 23–30, and compared them with the results shown in Figure 2 of the manuscript (> 730 hPa). Arctic dust INP concentrations are sensitive to the choice of vertical range, whereas Arctic MOA and bioaerosol INP concentrations are less sensitive. Overall, the spatial distribution patterns of Arctic INPs remain similar across the different vertical ranges.

With the current results, it is not possible to evaluate the sensitivity of the results to the choice of temperature range.

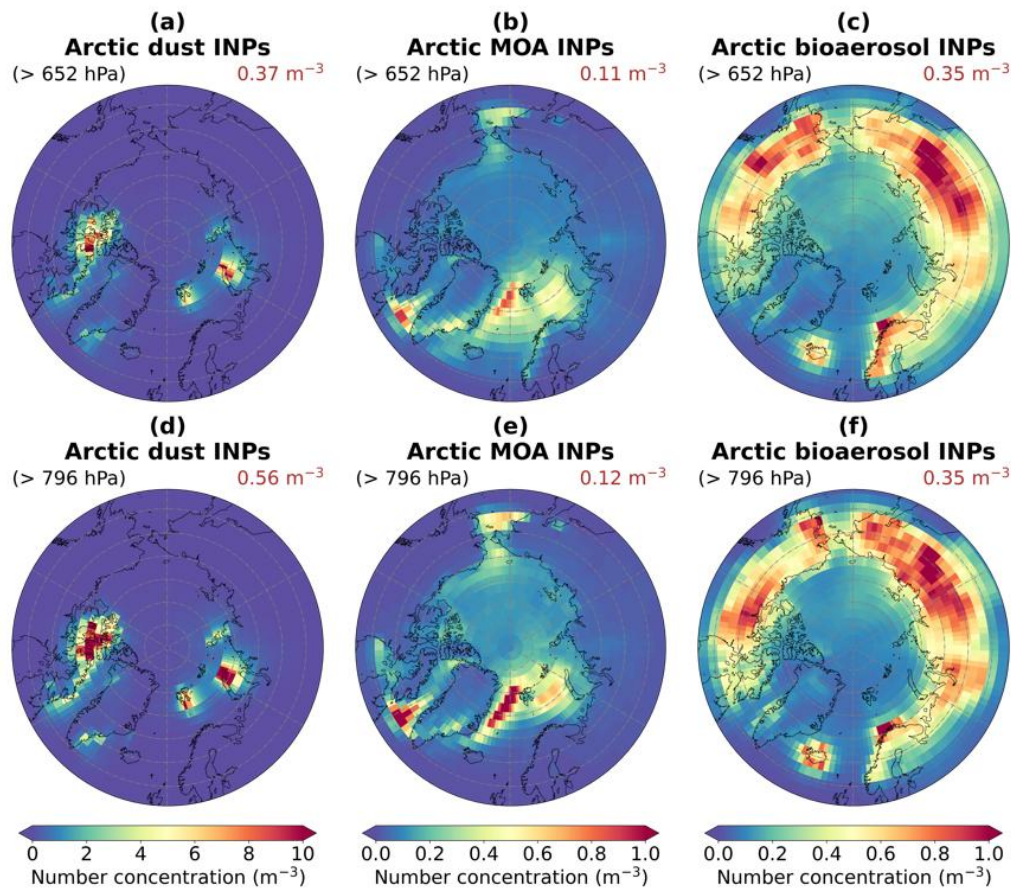


Figure R4. Spatial distributions of INP number concentrations of Arctic dust, Arctic MOA, and Arctic bioaerosols in the Arctic, averaged over 1981–2020. The upper row (a–c) shows values vertically averaged over pressure levels greater than 652 hPa, and the lower row (d–f) over pressure levels greater than 796 hPa. The numbers in the upper right corner of each panel represent the corresponding 40-year mean values over the Arctic.

- Fig. 4: To support this result or add additional value to it and the corresponding discussion, please add (can also be in the Appendix):

- The same figure but for different seasons. That would help to see if there is a connection between INP values and snow/sea ice cover.

- Add the same figures for dust, MOA, bioaerosols and non-Arctic INPs - it would be great to see a map where transported aerosols matter for Arctic INP.

We have calculated and plotted the seasonal spatial distributions of the INPs for each species and have added the following description to Section 3.2 of the manuscript.

L227 The vertically averaged INP concentrations in lower tropospheric clouds are 0.46 m^{-3} , 0.11 m^{-3} , and 0.35 m^{-3} for Arctic dust, Arctic MOA, and Arctic bioaerosols, respectively (Fig. 3g–i). Arctic dust INPs are mainly distributed over islands in the central

Arctic Ocean during summer and fall (Fig. S3). Arctic MOA INP concentrations are highest in winter, mainly over perennially ice-free ocean regions such as the Greenland Sea and the Norwegian Sea, and are nearly absent in summer because of higher temperatures (Fig. S4). Arctic bioaerosol INP concentrations are highest in fall and are distributed mainly over land regions, particularly northern Russia (Fig. S5).

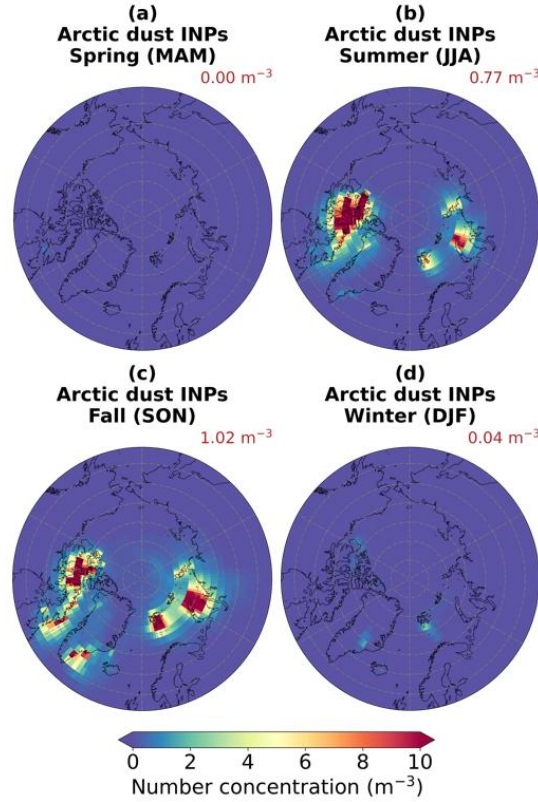


Figure S3. Seasonal spatial distributions of Arctic dust INP number concentrations in the Arctic lower troposphere (> 730 hPa) during 1981–2020, for (a) spring (MAM), (b) summer (JJA), (c) fall (SON), and (d) winter (DJF). The numbers in the upper right corner of each panel indicate the 40-year mean averaged over the Arctic lower troposphere.

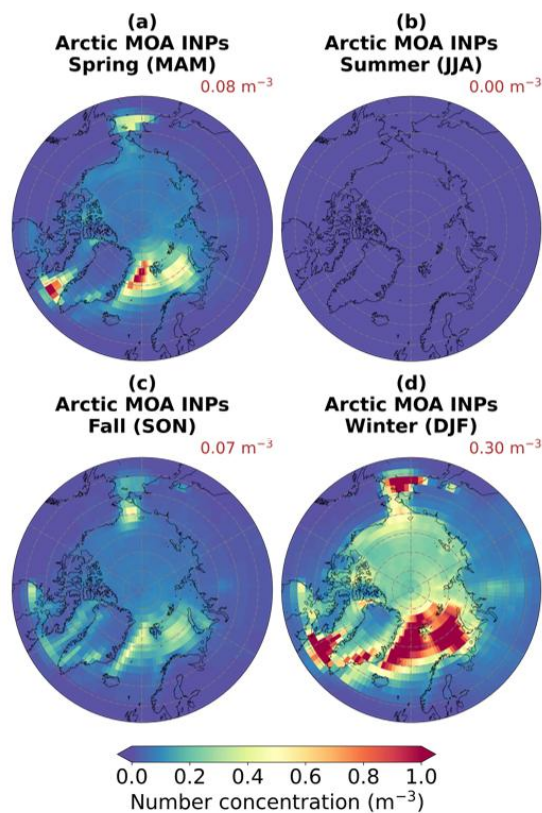


Figure S4. Seasonal spatial distributions of Arctic MOA INP number concentrations in the Arctic lower troposphere (> 730 hPa) during 1981–2020, for (a) spring (MAM), (b) summer (JJA), (c) autumn (SON), and (d) winter (DJF). The numbers in the upper right corner of each panel indicate the 40-year mean averaged over the Arctic lower troposphere.

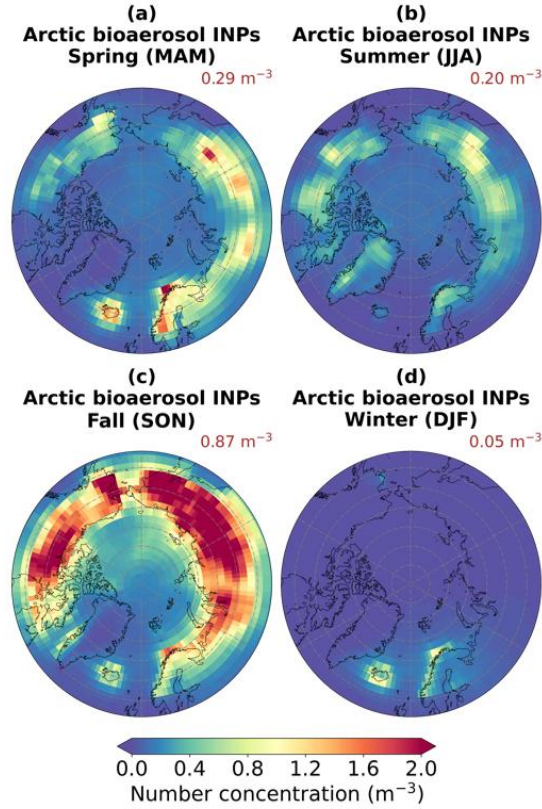


Figure S5. Seasonal spatial distributions of Arctic bioaerosol INP number concentrations in the Arctic lower troposphere (> 730 hPa) during 1981–2020, for (a) spring (MAM), (b) summer (JJA), (c) autumn (SON), and (d) winter (DJF). The numbers in the upper right corner of each panel indicate the 40-year mean averaged over the Arctic lower troposphere.

We have also added the following description regarding the seasonal contributions of Arctic and non-Arctic INPs, and the corresponding figures have been added to the SI.

L279 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.

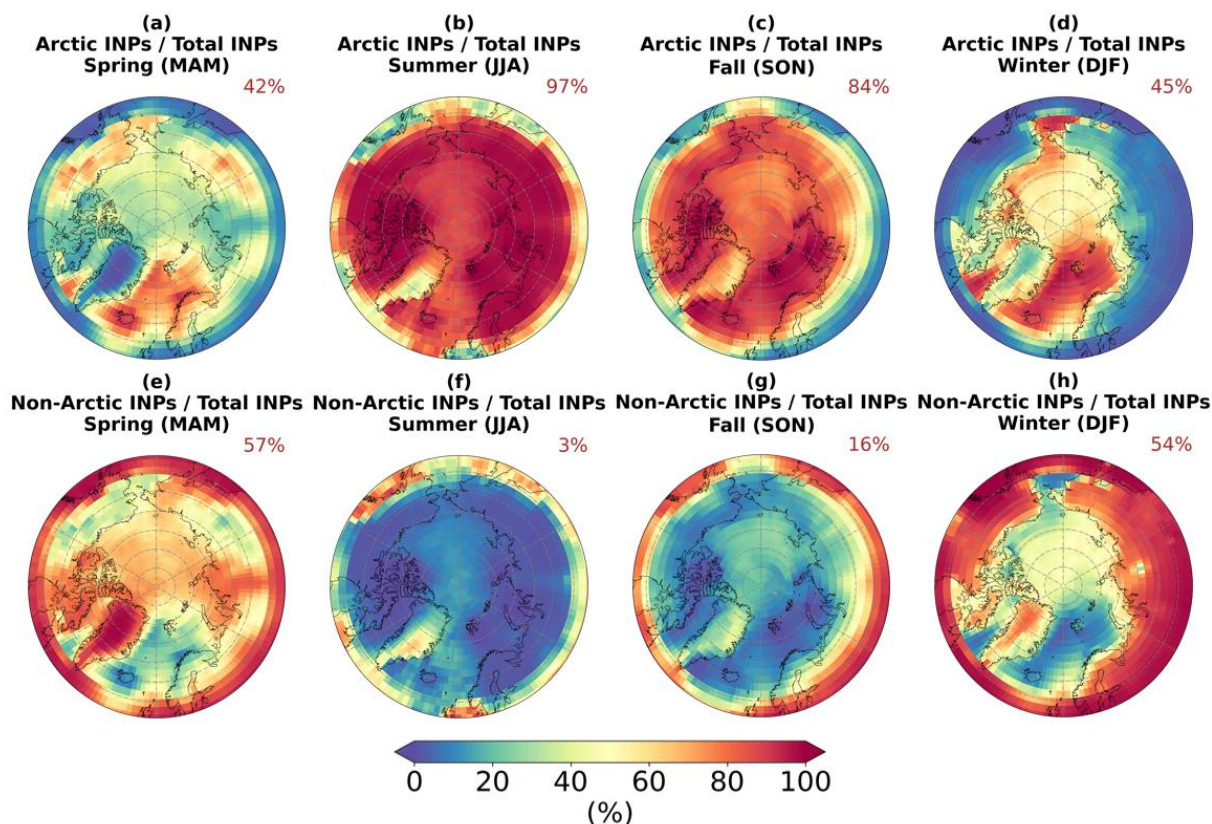


Figure S10. Seasonal spatial distributions of the contributions of (a–d) Arctic INPs and (e–h) non-Arctic INPs to total INPs in the Arctic lower troposphere (> 730 hPa) during 1981–2020 for spring (MAM), summer (JJA), fall (SON), and winter (DJF). The numbers in the upper right corner of each panel indicate the 40-year mean averaged over the Arctic lower troposphere.

- Fig. 4: Same as for Fig. 2: How much does the choice of vertical level influence the results? The level should differ quite a bit between non-Arctic transported aerosol, Arctic transported aerosol and Arctic local aerosol.

Figure R5 shows the spatial distributions of the vertically averaged contributions of Arctic dust, Arctic MOA, Arctic bioaerosols, and Arctic INPs to total (Arctic + non-Arctic) INPs for pressure levels of > 652 hPa and > 796 hPa. These ranges correspond to adding one model layer above or removing one model layer from the >730 hPa range used in the main analysis, respectively. Consistent with our response regarding Figure 2, the contribution of Arctic dust INPs is sensitive to the choice of vertical range, whereas those of Arctic MOA and Arctic bioaerosols are less sensitive. Although the Arctic mean contributions vary among the three vertical ranges, their spatial distribution patterns remain largely consistent.

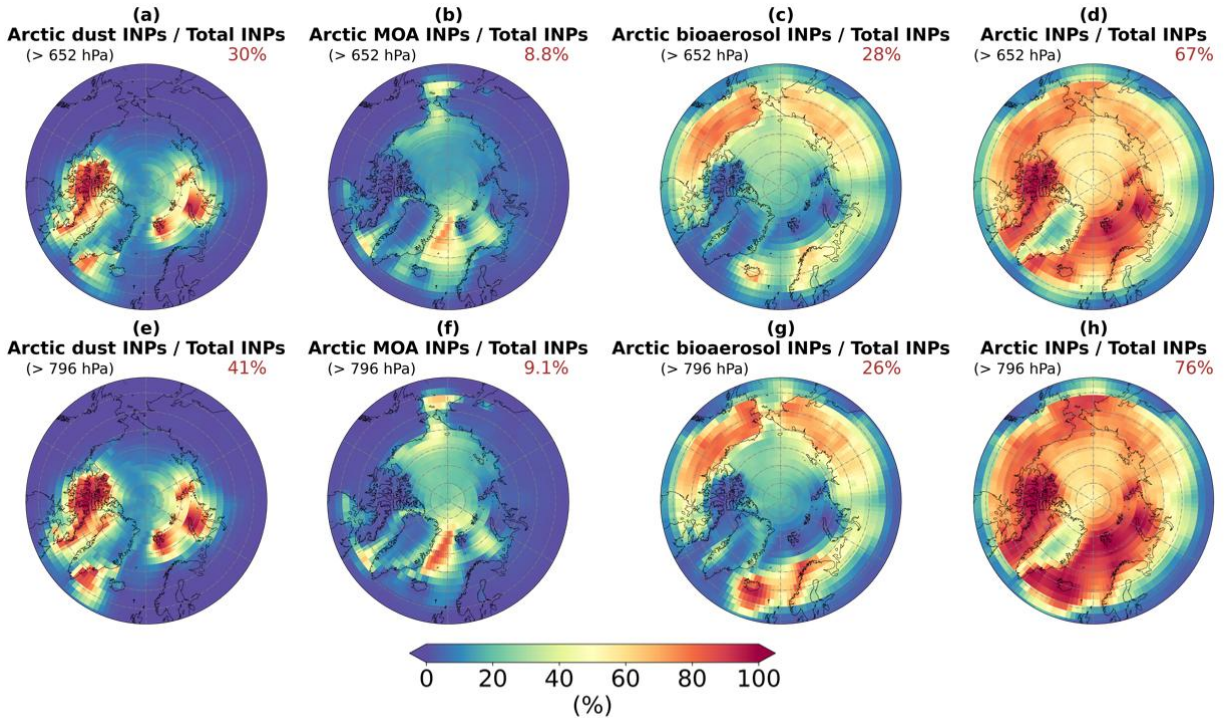


Figure R5. Spatial distributions of the contributions of Arctic dust, Arctic MOA, Arctic bioaerosols, and Arctic INPs to total (Arctic + non-Arctic) INPs for (a–d) pressure levels > 652 hPa and (e–h) pressure levels > 796 hPa during 1981–2020. The numbers in the upper right corner of each panel are the 40-year mean contributions averaged over the Arctic lower troposphere.

- Fig. 4: I guess you don't have saved instantaneous temperature binned output, so it is difficult to request this afterwards, but if there is this kind of output: it would be super interesting to see this results for different temperature bins.

Unfortunately, instantaneous temperature-binned INP output was not saved in our simulations, so we cannot provide the results for different temperature bins.

- Section 3.5: This section disturbed the flow of the last part of the paper. I think the conclusion of this section and the findings are really important. However, the authors should consider shifting this section to the appendix and just tie the conclusions into existing (other) text to keep the flow.

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.

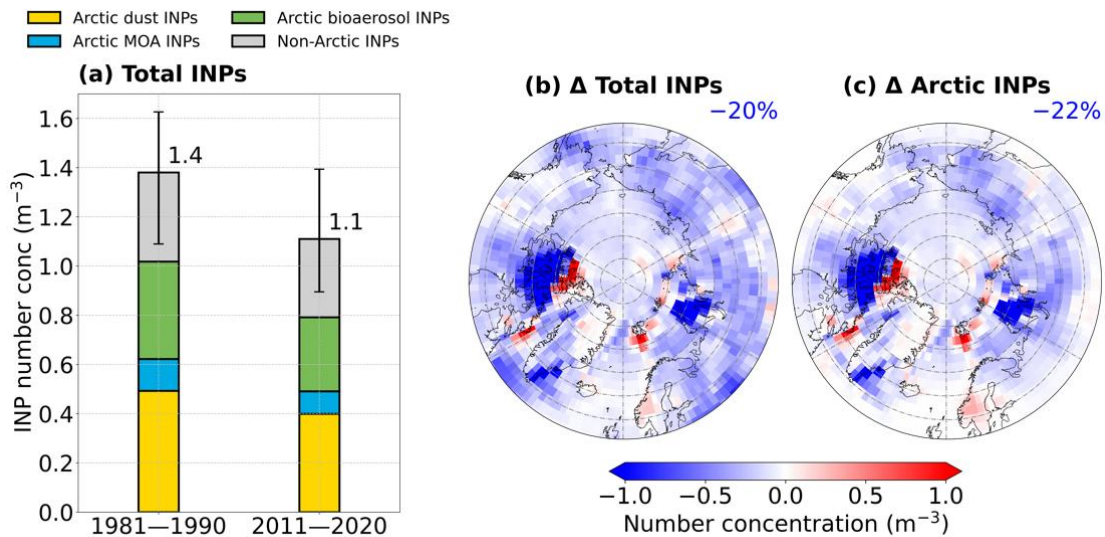


Figure 9. Decadal changes in INP number concentrations in Arctic lower tropospheric clouds (> 730 hPa) between 1981–1990 and 2011–2020. (a) Mean INP number concentrations for the two periods. (b–c) Spatial distributions of changes in INP number concentrations in clouds for (b) total INPs and (c) Arctic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

- Data availability: Nowadays data should be made available, so please consider sharing at least the processed data used for the figures (more data/not averaged etc. is of course also appreciated).

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.

Minor and technical comments:

- line 41: You write originating from plants here, is it not rather algae och marine species (plant might be a confusing word)?

We agree that “plants” may be too restrictive in this context, as bioaerosols can originate from both terrestrial and marine biological sources. We have therefore revised the wording as shown below.

***L45** In addition, bioaerosols from terrestrial and marine biological sources are recognized as important sources of INPs that are active at relatively high temperatures ($\geq -15^{\circ}\text{C}$) (Kawana et al., 2024; Pereira Freitas et al., 2023; Šantl-Temkiv et al., 2019).*

We have also clarified in the Methods section that our model considers only terrestrial bioaerosols.

***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.*

- line 45: You can remove the sentence "For example...".

Thank you for your suggestion. We considered removing this sentence, but we believe it is useful to retain it because it helps illustrate the differences in INA among aerosol species.

- line 58: The sentence on the Matsui et al. study does not really make sense in the current form (or I don't understand it).

We have rephrased this sentence as follows.

***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.*

- line 145: You write that the dust emissions are likely overestimated - can that be checked?

Figure S3 of Matsui et al. (2024) shows that, among observation sites, the dust mass concentration is overestimated by more than one order of magnitude only at Zeppelin, Svalbard. This suggests that dust emission may be overestimated in the vicinity of Svalbard.

- line 145-147: In my opinion your argumentation here does not make sense. The dust emissions are likely overestimated which in turn leads to an overestimation of dust INP for the Svalbard location. That sounds reasonable. However, I don't understand why the INP parameterization is important here - that should not be affected by an overestimation of dust emissions (it just propagates the error).

"These results" in this sentence does not refer specifically to the Svalbard results, but rather to the results from all observation sites discussed above. To avoid confusion, we have revised the wording as follows:

L206 In summary, the comparison between our model and these Arctic observations shows that simulated Arctic INP concentrations are sensitive to the choice and combination of INP parameterizations for different aerosol species.

- Fig. 1: Why is there one location (Northern Norway) with a lot smaller/no variability?

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.

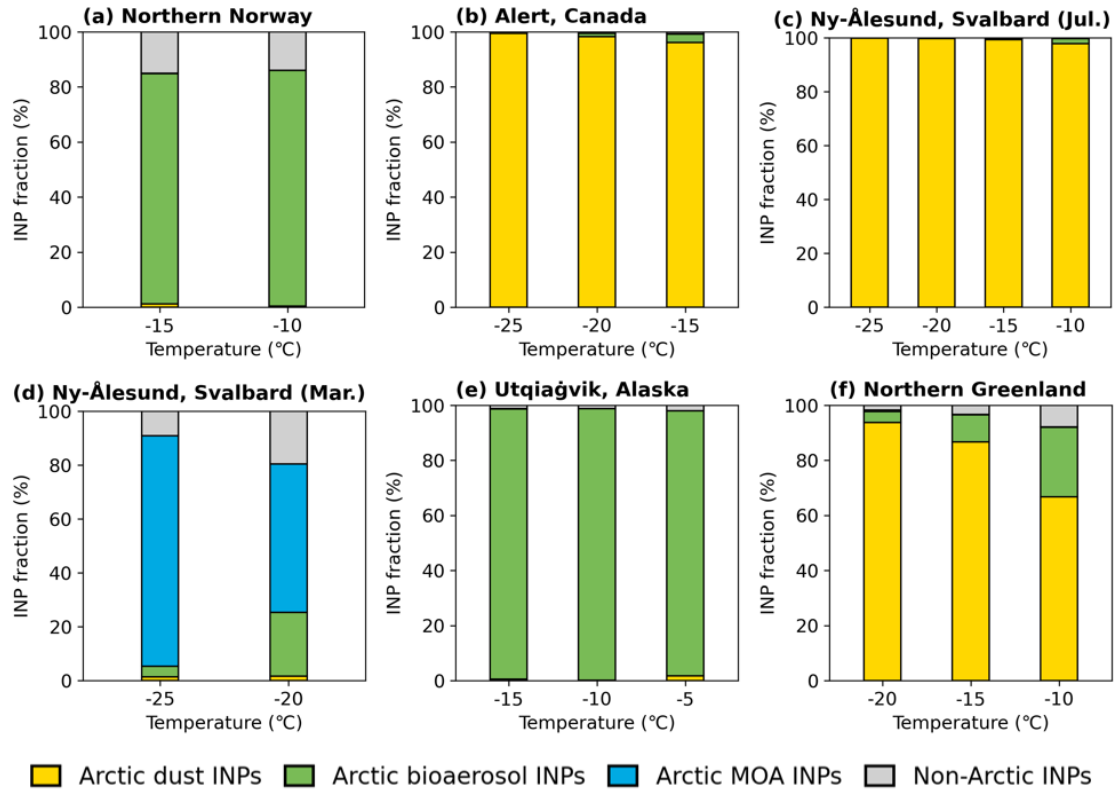


Figure 2. Fractions of Arctic dust INPs (yellow), Arctic bioaerosol INPs (green), Arctic MOA INPs (blue), and non-Arctic INPs (gray) in the total INP number concentrations simulated in the Base simulation at each observation site and temperature.

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, Alaska	6.68 ± 7.44 (CV = 111.5%)	6.17 ± 1.61 (CV = 26.0%)	1.33e+04 ± 1.82e+03 (CV = 13.7%)
Northern Greenland	99.7 ± 129 (CV = 129.2%)	1.47 ± 0.491 (CV = 33.3%)	123 ± 65.7 (CV = 53.5%)

- Fig. 1: The data points are a mean over 9 years? Could be specified in the caption.

The data points represent the mean observed INP number concentrations and the 10-year mean simulated INP number concentrations for the corresponding observation month(s) during 2010–2019. We have revised the caption of Figure 1 as follows:

Figure 1. 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.

- Fig. 1: How big were the temperature bins for the simulated data that were used to derive the simulated INPC at one specific T?

No temperature binning was applied. We used the observation temperatures shown on the x-axis as fixed temperatures in the offline calculation of INP number concentrations.

- Sect. 3.2: How were the vertically mean INPC calculated?

We calculated the mean INP number concentration in the Arctic lower troposphere (> 730 hPa) by averaging INP number concentrations (m^{-3}) over three-dimensional grids, weighted by layer thickness and grid-cell area.

- Line 197ff: I am not sure if you can make this statement.

We have revised some of the overstated wording.

L256 *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.*

- Fig. 5: I am surprised that there is never areas with 0 Arctic INPs? Is that because it is a average value over the whole time span?

The data shown in Figure 6 in the revised manuscript represent averages over the entire 40-year period, and therefore there are no areas where the contribution of Arctic INPs is exactly zero. Because the lowest color range represents 0–10%, some regions within this color range could have contributions very close to zero.

- Fig. 5: The monthly mean T can confuse. The INP values are not calculated based on this temperature.

In our simulations, INP concentrations are calculated based on the ambient temperature at each timestep (every 30 minutes). The INP calculation is performed for temperatures ranging from -37°C to -5°C , and the ambient temperature used in the calculation varies over time. In contrast, the temperature contours shown in Figure 5 of the original manuscript represent the 40-year mean temperature and show the temporal variation and vertical distribution of Arctic-mean temperature. We have added the following statement to the captions of Figures 4 and 6 of the revised manuscript 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 .

- Fig. 5: Here temperature binned would also be great. This figure in the current form is a bit hard to read because what is seen is based on a mixture of aerosol profile and temperature at the level where Arctic aerosols exist.

Temperature-binned INP output was not saved in our simulations, and therefore results for different temperature bins cannot be provided. In this figure and throughout this study, what we primarily present and discuss is the combined influence of the emission effect and the temperature effect on INPs, and the results therefore reflect both the aerosol profiles and temperature.

- Line 230f: I don't agree with that these results show a strong correlation... You would need to calculate this and I don't see something like that in the paper?

Thank you for pointing this out. We have revised the wording to avoid implying a statistically evaluated correlation.

L305 *These results illustrate the close relationship between Arctic warming and reductions in snow and sea ice cover.*

- Fig. 6: Can you add here the spatial distribution from one period (1981-1990 is probably a good choice) or even both as well? That would be a nice extra information in addition to the change plot.

Following the suggestion, we have added the spatial distributions for 1981–1990 and 2011–2020 to the Supplementary Information, as shown below.

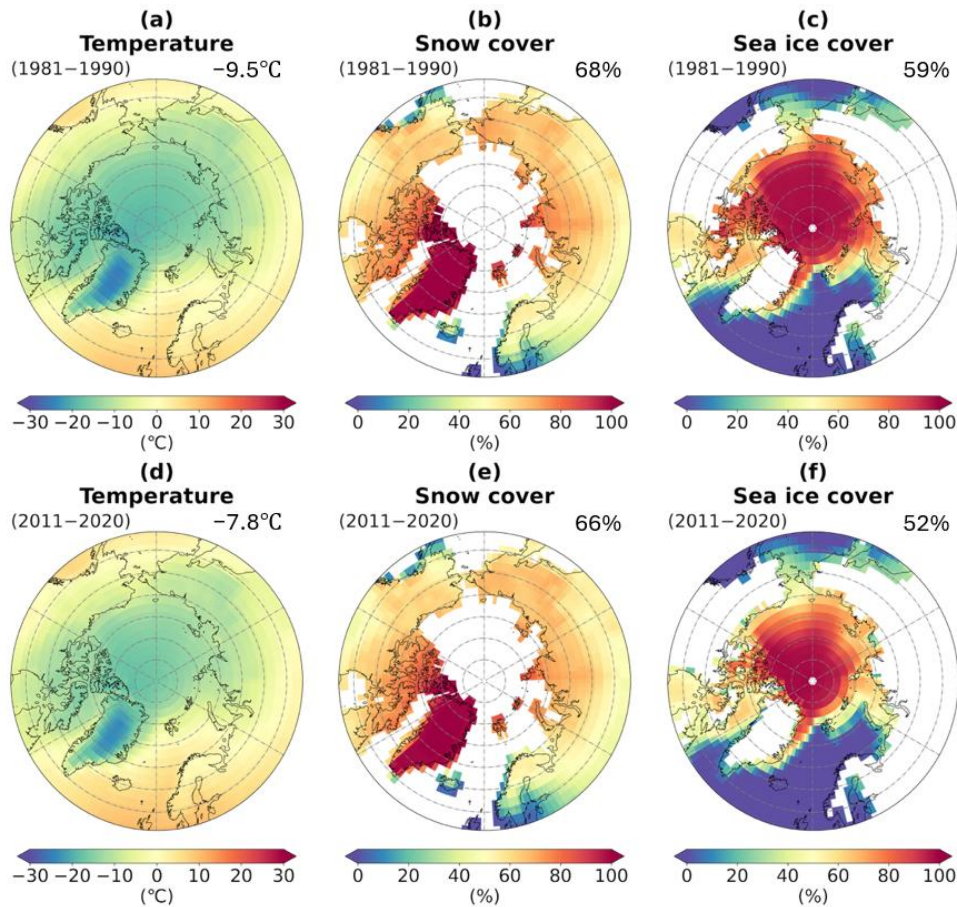


Figure S12. Spatial distributions of (a, d) surface air temperature, (b, e) snow cover fraction, and (c, f) sea ice cover fraction in the Arctic, averaged over (a–c) 1981–1990 and (d–f) 2011–2020.

- line 247: Write "change of mean values" (as used later) instead of "rate of change".

We used “percentage changes” here to improve clarity, and we have revised the relevant sentences in the captions of Figures 8 and 9 as follows.

Figure 8. The numbers in the upper right corner of each panel represent the percentage changes in mean values in the Arctic lower troposphere between 1981–1990 and 2011–2020.

Figure 9. In panels (b–c), the numbers in the upper right corner indicate percentage changes in mean values in the Arctic lower troposphere between 1981–1990 and 2011–2020.

- line 249: Agreed that if there is a correlation it would show in your figure. However, you did not do a correlation analysis and you do not show spatial correlation here, so please rewrite.

As the reviewer pointed out, we have not conducted a formal correlation analysis, and we have therefore revised the sentences as follows:

***L325** In our model, dust and bioaerosols are emitted from snow- and ice-free land surfaces, whereas MOA is emitted from ice-free ocean surfaces. Their emissions are therefore linked to changes in snow and sea ice cover. Figure 8a–c also shows the spatial correspondence between the increase of aerosol emissions and the reduction of snow and sea ice.*

- line 258-264: Add some explanation already here?

We added a brief explanation to aid understanding.

***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.*

- line 269-270: This is very confusing written: it is not driven by a reduction of INP (which I phrased like that would intuitively read as reduction of aerosols), but a change in temperature that affects the INP efficiency.

We have revised this sentence as follows.

***L351** These results indicate that changes in the total INP number concentrations in the Arctic lower tropospheric clouds over the past 40 years are driven largely by decreases in Arctic INPs.*

To avoid ambiguity, we clarified at key points in the manuscript that the INPs we discuss refer to INPs within clouds.

- Fig. 8: I would move the LowBac part here to the Appendix.

Please refer to our response to the comment on Section 3.5.

- Fig. 9: This is a mean over the whole time period? How variable is the result?

This figure provides an overview of the previously presented results, showing the changes from the 1981–1990 mean to the 2011–2020 mean. To avoid misinterpretation, we have removed this figure.

- Code availability: I would remove "reasonable" request (upon request is enough).

Done.

- Line 367-369: You could explain this more/elaborate on this more.

We have expanded this sentence with a more detailed explanation.

***L405** A better understanding of the interplay between the temperature effect and the emission effect and their influences on Arctic clouds and radiation is important for improving predictions of Arctic climate change. These findings provide a foundation for future research on INP-related processes and their effects on Arctic climate.*

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