Review:

"Ice-nucleating particles in Greenlandic glacial outwash plains"

Summary:

In their manuscript, Bergner and colleagues investigated ice-nucleating particles in southern Greenland along glacier runoffs during summer field campaigns in 2023 & 2024. In general, they aimed to understand whether the number of INPs present in southern Greenland is comparable to those observed at other high latitude sites on the globe. They collected soil samples along glacier outwash zones and tested the resulting soil-suspensions in immersion freezing mode. In addition, airborne particles were collected onto filters, which were extracted in the lab and analysed in accordance to the suspensions. Their results indicate that organic and biological materials contributed significantly to the INP population in both soil and air samples. Notably, the data shows no relationship between INP abundance and distance from the glacier along the outwash zone. In contrast to previous studies, they could not identify any correlation between the amount of INPs and meteorological conditions. However, they found that the air samples were influenced by local emissions.

This is comprehensive study that presents a large data set on INPs in southern Greenland, supported by detailed analytical measurements. In general, this work is of interest to the ice nucleation community and suits publication in ACP after addressing the following minor revisions.

GENERAL COMMENT:

How comparable are bulk dust INPs, collected from the top 1 cm of soil, with the 'microbiology' samples taken from the top 5 cm? How much does the microbial composition vary within these soil layers, and could this affect the interpretation of the results?

SPECIFIC COMMENTS:

Abstract:

Line 27-28: "Atmospheric INP concentrations above -20 °C were higher at the outwash plain sites compared to a nearby fjord site, […]" – It is unclear to me which sites are considered fjord sites? The discussion in the main text focuses on the term 'outwash plain sites', but the term 'fjord sites' is not used consistently. Please clarify.

Line 33-34: "[…] This highlights the importance of region-specific dust characterizations for improving representation of cloud processes and climate impacts in the Arctic." It is unclear whether the authors mean that the physical and chemical characteristics of dust should be determined, or region-specific INP parameterizations are needed to improve our understanding of cloud processes. Please be more specific.

Introduction:

In general, the introduction gives a comprised overview of the current state of the art and identifies important knowledge gaps. Some sentences are rather long, which reduces readability. Consider dividing them into shorter, more focused statements to enhance clarity.

Line 37-38: Specify that this is true for mixed-phase clouds but keep in mind that INPs can influence heterogeneous ice nucleation below the mentioned temperature threshold of -38°C.

Line 44: Please clarify if the goal is to quantify the sources of INPs or quantify INPs themselves. I'd argue that the aim is to identify the sources and quantify INPs.

Line 52: How do you define "source" in this context? Since you mentioned a few lines earlier that high latitude dust can originate from distant regions, it may be clearer to refer here to 'location' rather than 'source'.

Methods:

Line 115: "[…] locations farther from the glacier have been exposed longer following glacial retreat […]" Could the authors add which kind of exposure they are referring to here.

Table 1: In case of a sample not being treated with neither heat nor H_2O_2, I would state that in the corresponding cell instead of leaving it blank.

Section 2.1.2.: It would be helpful to specify how far above the ground the filters were collected. While some photos in the Appendix provide some context about this, I think it is important to include this information in the main text.

Section 2.2.: How were the samples stored during the field campaign? Were the samples measured directly after collection or were they shipped to a laboratory? If shipment took place, under which conditions were the samples shipped? Please provide details about storage and sample handling in this section and how this could have effected the results.

Section 2.2.: How easily were the soil samples suspendable in water? Please give more details on this and describe possible limitations.

Equation 1: Please add a step-by-step derivation of this equation to the Appendix. I also think Vali, 2019 would be the better reference here.

Line 179: I believe "d" is a dilution "factor" not the ratio.

Line 180: According to Vali, 2019 the terminology for ns is "active site density" and is defined as '[…]"the number of sites causing nucleation per unit surface area of the IN" – In the manuscript, nm is referred to as 'ice-active mass site density', which is slightly inconsistent with the proposed

terminology. I recommend revising nm and ns, stating them as 'ice-active site density per mass or per surface area'.

Line 198: "Heat treatment denatures proteins" – Please add more content to this statement. What is the minimum temperature required for proteins to unfold? Is this the same for all proteins? In general, I am missing the discussion on the limitations of the treatments. For example, Daily et al., 2022 showed that heat treatment is not entirely selective to proteinaceous INPs but can also alter the ice-activity of certain dusts, like quartz and plagioclase feldspar. Please add some discussion about this.

Line 202-204: If H_2O_2 is exposed to UV radiation in water, OH radicals are generated. This important detail is currently missing in the main text. Also, mention that catalase was added specifically to prevent freezing point depression, which would occur if residual H_2O_2 remained in the sample.

Line 233: Please add the reasoning why you chose a threshold of -15°C?

Results & Discussion:

The structure of the 'Results & Discussion' section is somewhat inconsistent, as discussion is often presented before the results. Typically, results should be described first, followed by their discussion.

Line 362: Since you discuss how vegetation might influence your INP spectra, this aspect could be expanded further. Simply stating that fungal spores contribute is rather limited. In general, plant surfaces are well known to host INPs. For example, studies have shown that INPs can be washed off leaves during rainfall (Conen et al., 2025; Seifried et al., 2020). Conen et al. hypothesized that surfactant excretion by INP-producing bacteria leaves INPs on the plant surfaces. In addition, lichens growing on tree bark are known to be a source of vegetation-derived INPs (Kieft and Lindow, 1988).

Figure 4 and all figures that contain box plots: Add details explaining the box plots, specifying what the median, quartiles, and whiskers represent. Usually, outliers are visible for these types of plots. Were they excluded?

Line 396-397: I don't fully agree with this statement. According to the INP spectra in Figure 6a, the *hill* site also shows high INP concentrations between -8 and -20°C. It is even higher at the warmer temperatures than for the *col* site.

Line 410: Please add Diehl et al., 2001 as a reference.

Line 424-429: Please add an explanation on what D10 and D15 represents.

Line 469-470: What do you mean by 'threshold velocity'? Please expand this argument.

Figure 8a-c: N_INP(L-1) represents the cumulative number of ice nuclei per litre of air. At −15 °C on day 1, there are 10^-1 L^-1 at station c*ol*, but no data is shown for *col* at -20 °C. Please clarify.

Appendix:

Figure A6: I don't see the data for unfiltered water. In the legend it is stated as being depicted as grey lines.

Figure B9: For the first column, I assume nm stands for the sum of all nm? Please clarify.

Figure B11: How did you determine that these particles are mineral dusts, come from marine sources or are from long-range transport? Did you perform any additional analysis on those particles besides SEM?

Figure B12: Adjust the legend and re-name "clean marine" to a more specific description.

Figure B14: It is unclear what the bright brown lines indicate. Please clarify.

Are Figure C4 and Figure C2b the same? If yes, only show it once.

Typos etc.:

Line 263: typo for potassium feldspar (K-feldspar)

Line 219: Tobo reference is missing a bracket

References:

Conen, F., & Einbock, A. (2025). Release of ice-nucleating particles from leaves during rainfall. *The Science of Nature*, *112*(2), 29.

Daily, M. I., Tarn, M. D., Whale, T. F., & Murray, B. J. (2022). An evaluation of the heat test for the ice-nucleating ability of minerals and biological material. *Atmospheric Measurement Techniques*, *15*(8), 2635-2665.

Diehl, K., Matthias-Maser, S., Jaenicke, R., & Mitra, S. K. (2002). The ice nucleating ability of pollen:: Part II. Laboratory studies in immersion and contact freezing modes. *Atmospheric Research*, *61*(2), 125-133.

Kieft, T. L. (1988). Ice nucleation activity in lichens. *Applied and environmental microbiology*, *54*(7), 1678-1681.

Seifried, T. M., Bieber, P., Felgitsch, L., Vlasich, J., Reyzek, F., Schmale III, D. G., & Grothe, H. (2020). Surfaces of silver birch (Betula pendula) are sources of biological ice nuclei: in vivo and in situ investigations. *Biogeosciences*, *17*(22), 5655-5667.

Vali, G. (2019). Revisiting the differential freezing nucleus spectra derived from drop-freezing experiments: methods of calculation, applications, and confidence limits. *Atmospheric Measurement Techniques*, *12*(2), 1219-1231.