Reviewer responses are given in blue.

Reviewer 1

The study presented by Barry et al. investigates the seasonal cycle of INP concentration and bioaerosols based on measurements taken onboard the research vessel Polarstern over a one-year period. They find significant variability in the bacterial and fungal composition, suggesting a mixture of local, regional, and long-range transported bioaerosols. Moreover, the authors state that biological particles contribute significantly to the INP population throughout the year, dominating it in summer.

The study is very well written and presents an interesting dataset from a unique campaign. However, my major concern is about the methods used to infer information about the biological, organic, and inorganic content of the INP samples using heat treatments and H_2O_2 digestion, and consequently, how the results of these treatments are discussed. I am aware that such treatments are frequently used nowadays to investigate contributing species to the INP population. However, recent studies have shown that wet heat treatments can also alter the ice nucleation ability of some mineral particles, while some biogenic INPs are not affected by heat treatments (Daily et al., 2022). Using this method alone to infer contributions from biological aerosols to INPs is therefore not sufficient

Response to Major concern: We address this concern in detail in the response below to the question about Figure 2. We have also added text to the manuscript accordingly to explain prior tests reported to confirm the interpretation of the treatments.

Minor

Thank you to Reviewer 1 for the helpful responses to improve this manuscript. We have addressed all concerns and changed the text and figures to have greater clarity.

Abstract: More information about the measurement methods could be given here (e.g., how INPs were measured, the temperature range and the time resolution of the measurements.

We added: "with 3-day filters for amplicon sequencing and cumulative INP concentrations from -5 to -30 °C." (Line 17)

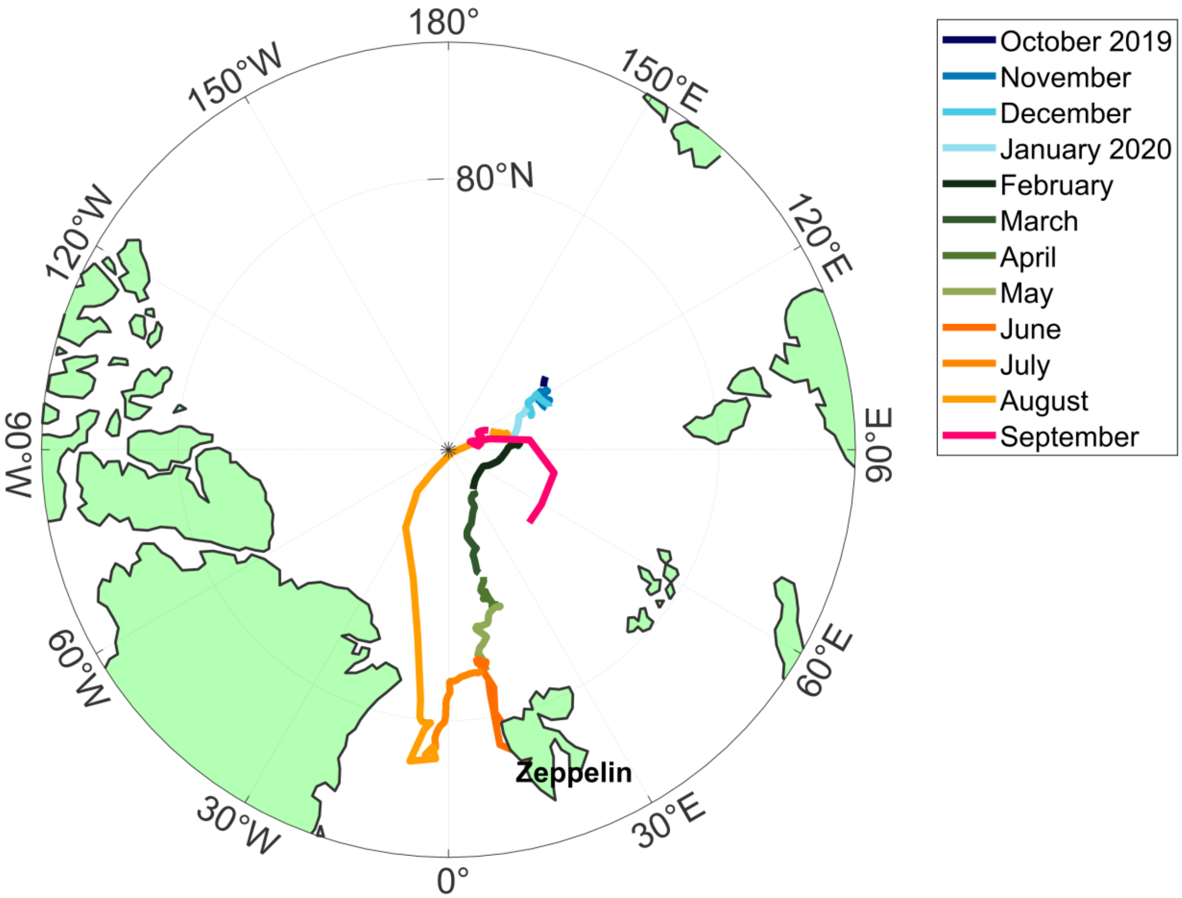
Line 55: „campaign" is double.

Thank you, this is corrected.

Lines 62 – 64: Given that the abundance of INPs and bioaerosols might be different depending on the sampling location within the Arctic, a map of the legs could be helpful.

We have added the combined ship track for the period of time when samples were collected, that is now Figure S1.

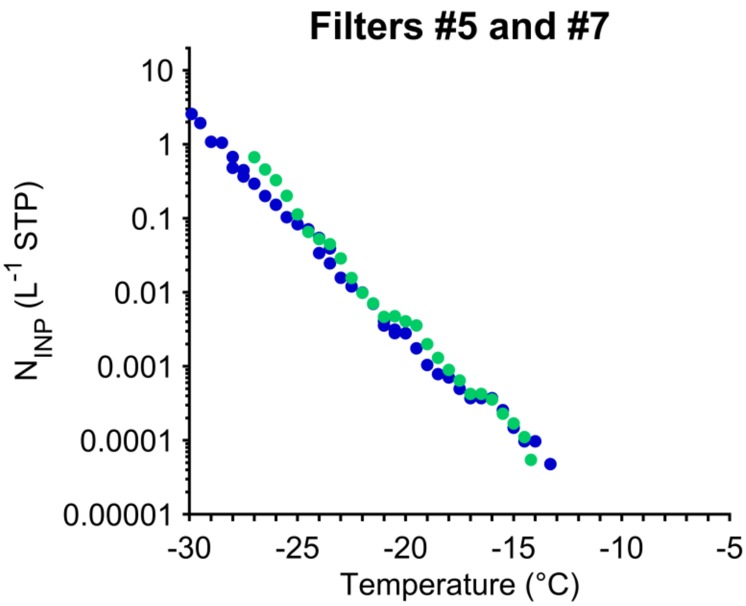
"The other periods were time when the ship was in transit, but we include collected samples between October 27, 2019-September 25, 2020 (Figure S1)." Lines (65-66)



Line 74: With a three-day time resolution of the filter samples, I assume that impact from the reserach vessel itself can occur. How could this impact the results of the INP and DNA analysis?

For INPs, the effect of the research vessel from soot contamination is likely the main concern (soot grayness will also correlate with general level of stack contamination), but we did a test showing that two filters with different degrees of soot contamination (one slight and the other moderate) collected at the same time of year had virtually identical INP concentrations (i.e., the additional soot loading did not increase INPs). It has been shown that soot is a poor INP in the immersion mode (Kanji et al. 2020). For DNA, we are mostly concerned with biological contamination from the ship, as common human contaminants, such as E. coli, exist. For those we had proceeded with a rigorous blank ASV removal algorithm that is detailed in Lines 132-137. It will be impossible to remove all contaminants for either INP or DNA, but we believe we have controlled for this the best we can, without artificially influencing the samples.

Kanji, Z. A., Welti, A., Corbin, J. C., & Mensah, A. A. (2020). Black carbon particles do not matter for immersion mode ice nucleation. Geophysical Research Letters, 46, e2019GL086764. https://doi.org/10.1029/2019GL086764



Line 178: As part of the data is presented in Creamean et al. (2022), it might be worth to mention the difference between this and their study.

We have added details: “First, we present the seasonal cycle of INP composition for MOSAiC, partially presented in the Creamean et al. (2022) supplement to add context to their size-resolved data.” Lines (180-181)

Line 182: Are there measurement or modeling information about the Arctic haze occurrance during this year? And does it align well with the Fig. 2?

The Arctic haze season peaked earlier during the MOSAiC season, which generally aligns with Figure 2.

We have added: “The Arctic haze season during MOSAiC was stronger and peaked earlier than normal (January and February), with a large positive Arctic Oscillation phase, and which could have contributed the large inorganic INP fractions seen during this time colder than -20 °C (Boyer et al., 2023).” Lines (188-190)

Boyer, M., Aliaga, D., Pernov, J. B., Angot, H., Quéléver, L. L. J., Dada, L., Heutte, B., Dall'Osto, M., Beddows, D. C. S., Brasseur, Z., Beck, I., Bucci, S., Duetsch, M., Stohl, A., Laurila, T., Asmi, E., Massling, A., Thomas, D. C., Nøjgaard, J. K., Chan, T., Sharma, S., Tunved, P., Krejci, R., Hansson, H. C., Bianchi, F., Lehtipalo, K., Wiedensohler, A., Weinhold, K., Kulmala, M., Petäjä, T., Sipilä, M., Schmale, J., and Jokinen, T.: A full year of aerosol size distribution data from the central Arctic under an extreme positive Arctic Oscillation: insights from the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, Atmos. Chem. Phys., 23, 389–415, https://doi.org/10.5194/acp-23-389-2023, 2023.

3: The marine impact in January is quite high as compared to the other winter months, is there an explanation for it?

Blowing snow is one explanation, as there were several events during January (Bergner et al. 2025) that aligned with a high abundance of marine taxa, especially collected in the January 15-18 filter. Particles in the snow could sublimate in the atmosphere. Transport of marine airmasses in the Arctic Haze is also possible, such as from deposition of sea spray and re-emission during blowing snow periods.

Nora Bergner, Benjamin Heutte, Ivo Beck, Jakob B. Pernov, Hélène Angot, Stephen R. Arnold, Matthew Boyer, Jessie M. Creamean, Ronny Engelmann, Markus M. Frey, Xianda Gong, Silvia Henning, Tamora James, Tuija Jokinen, Gina Jozef, Markku Kulmala, Tiia Laurila, Michael Lonardi, Amy R. Macfarlane, Sergey Y. Matrosov, Jessica A. Mirrielees, Tuukka Petäjä, Kerri A. Pratt, Lauriane L. J. Quéléver, Martin Schneebeli, Janek Uin, Jian Wang, Julia Schmale; Characteristics and effects of aerosols during blowing snow events in the central Arctic. *Elementa: Science of the Anthropocene* 3 January 2025; 13 (1): 00047. doi: https://doi.org/10.1525/elementa.2024.00047

Line 180: Similar to the explanation of „heat labile (presumably biological)", an explanation to heat stable organics and inorganics might help the reader to put this in context.

Thanks for the suggestion, we have added: "heat stable organics (e.g. from soil dust or sea spray), and inorganic (presumably mineral) (Fig. 2)." (Lines 182-183)

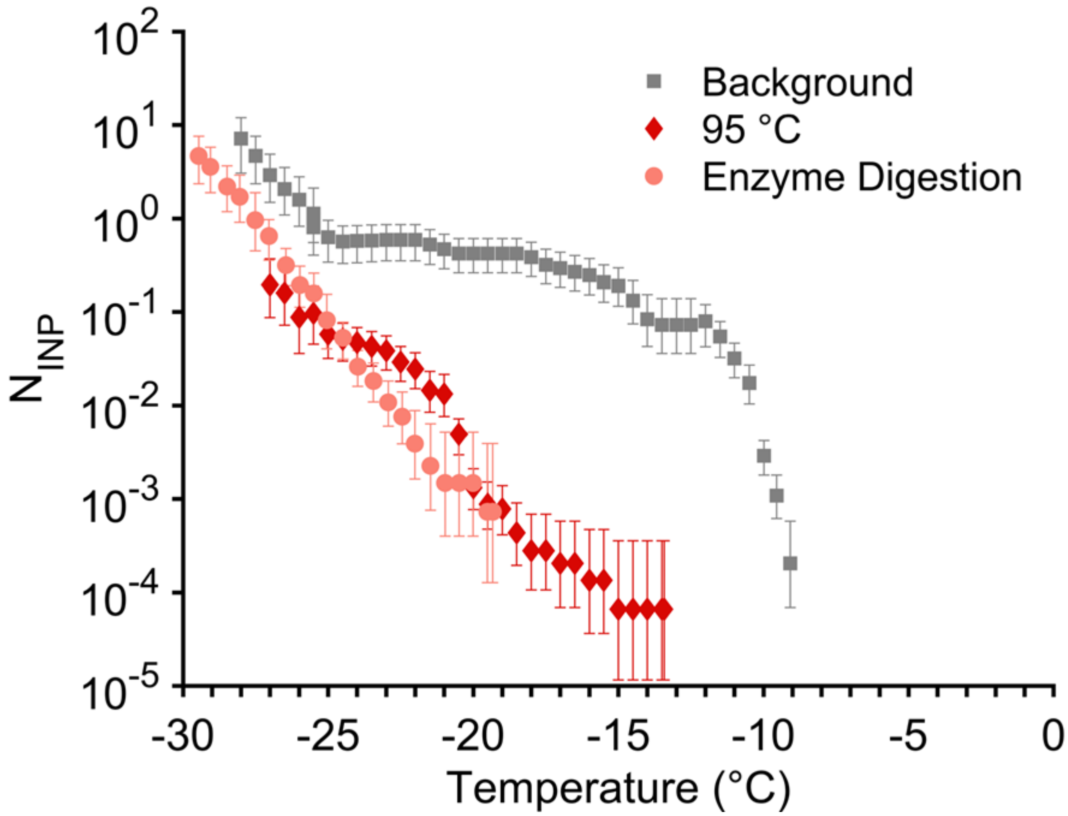
Figure 2: Sample Aug 2 seems to be different to the other summer samples, any explanation for it?

Yes, one potential explanation was found in the back trajectory analysis. We have added: "The August 2-5 filter was marked by lower concentrations and a lower fraction of heat labile INPs at -25 °C, which may have resulted from an airmass transition sampling air from predominantly over the ocean to over the sea ice (Fig. 6)." (Lines 184-186)

Figure 2: It is interesting to see that at T -25 °C in summer, also heat labile (biological) INPs are dominating the INP population, as this is a temperature range where mostly dust particles contribute to the INP population. Thus I am wondering if the treatments are really giving information about the inorganic or biological content (see my major concern). Are there other studies suggesting that dust (e.g., from local sources such as glacial dust) are not as important during this season? It is interesting as emissions of Arctic dust is largest in late spring summer, early autumn, depending on location (e.g., Bullard, 2012; Groot Zwaaftink et al., 2016). Is there any information about the abundance of dust particles during the here presented measurement period?

Thanks for your comment. There is one MOSAiC study, Ansmann et al. 2023, which found lidar retrievals of dust fraction of less than 5% throughout the MOSAiC year. We saw evidence of terrestrial influence at all times of year, despite a greater marine influence in the summer. Many of the terrestrial particles in summer can come from Arctic and glacial soil dust, so we are not suggesting that the INP contribution from this source is negligible. However, from previous work, we think that the main driver of the high INP activity in summer, even at colder temperatures, is attributed to the organic component instead of their mineral component. This has been shown through hydrogen peroxide digestion by Tobo et al. 2019.

Additionally, we have recently done a multi-enzymatic digestion comprising 6 cell wall enzymes (targeting bacteria, filamentous fungi and yeast) followed by a general protease to digest the liberated proteins and the proteins within them on an aliquot of a summer MOSAiC sample to show results comparable to those obtained with the 95 °C treatment. The 95 °C treatment has been done for samples for a variety of previous environments (McCluskey et al., 2018; Suski et al., 2018; Barry et al., 2021; Knopf et al., 2021; Testa et al., 2021, DeMott et al. 2025). We believe it provides a reasonable estimate of biological INPs in this location, and the best tool available at this point in time.



We will add this to Figure S9, and in the main text: "Additionally, we compared the difference between 95 °C heating and an enzymatic digestion on a summer sample (Figure S9) and found them to be comparable." (Lines 195-196)

As regards to the impact of H_2O_2 digestion likely effectively targeting inorganics such as mineral dust, evidence presented in Tobo et al. (2014), Hill et al. (2016), Suski et al. (2018) and DeMott et al. (2025) demonstrates equivalent impacts of heated peroxide digestion on the INP activity of bulk arable soils as for the use of dry thermal treatment at 300°C, and no impact of either method on some natural desert soils. Daily et al. (2022) found little impact of dry heating on mineral particles. Furthermore, the equivalency of the wet/heated peroxide treatment of filter collected ambient particles and dry 300°C treatment of free-flowing single ambient particles over the same collection periods in Suski et al. (2018) and DeMott et al. (2025) for two different environments suggests that the changes seen in INP spectra after treatment are due to impacts on organic INP components, leaving inorganics as the remnant INP contribution.

Ansmann, A., Ohneiser, K., Engelmann, R., Radenz, M., Griesche, H., Hofer, J., Althausen, D., Creamean, J. M., Boyer, M. C., Knopf, D. A., Dahlke, S., Maturilli, M., Gebauer, H., Bühl, J., Jimenez, C., Seifert, P., and Wandinger, U.: Annual cycle of aerosol properties over the central Arctic during MOSAiC 2019–2020 – light-extinction, CCN, and INP levels from the boundary layer to the tropopause, Atmos. Chem. Phys., 23, 12821–12849, https://doi.org/10.5194/acp-23-12821-2023, 2023.

Tobo, Y., Adachi, K., DeMott, P. J., Hill, T. C. J., Hamilton, D. S., Mahowald, N. M., Nagatsuka, N., Ohata, S., Uetake, J., Kondo, Y., & Koike, M. (2019). Glacially sourced dust as a potentially significant source of ice nucleating particles. Nature Geoscience, 12(4), 253–258. https://doi.org/10.1038/s41561-019-0314-x

McCluskey, C. S., Ovadnevaite, J., Rinaldi, M., Atkinson, J., Belosi, F., Ceburnis, D., Marullo, S., Hill, T. C. J., Lohmann, U., Kanji, Z. A., O'Dowd, C., Kreidenweis, S. M., & DeMott, P. J. (2018). Marine and Terrestrial Organic Ice-Nucleating Particles in Pristine Marine to Continentally Influenced Northeast Atlantic Air Masses. Journal of Geophysical Research: Atmospheres, 123(11), 6196–6212. https://doi.org/10.1029/2017JD028033

Suski, K. J., Hill, T. C. J., Levin, E. J. T., Miller, A., DeMott, P. J., & Kreidenweis, S. M. (2018). Agricultural harvesting emissions of ice-nucleating particles. Atmospheric Chemistry and Physics, 18(18), 13755–13771. https://doi.org/10.5194/acp-18-13755-2018

Barry, KR, Hill, TCJ, Levin, EJT, Twohy, CH, Moore, KA, Weller, ZD, Toohey, DW, Reeves, M, Campos, T, Geiss, R, Fischer, EV, Kreidenweis, SM, DeMott, PJ. 2021b. Observations of ice nucleating particles in the free troposphere from western US wildfires. Journal of Geophysical Research: Atmospheres 126: e2020JD033752. DOI: https://doi.org/10.1029/2020JD033752.

Knopf, D. A., and Coauthors, 2021: Aerosol–Ice Formation Closure: A Southern Great Plains Field Campaign. *Bull. Amer. Meteor. Soc.*, **102**, E1952–E1971, https://doi.org/10.1175/BAMS-D-20-0151.1.

Testa, B., Hill, T. C. J., Marsden, N. A., Barry, K. R., Hume, C. C., Bian, Q., Uetake, J., Hare, H., Perkins, R. J., Möhler, O., Kreidenweis, S. M., & DeMott, P. J. (2021). Ice Nucleating Particle Connections to Regional Argentinian Land Surface Emissions and Weather During the Cloud, Aerosol, and Complex Terrain Interactions Experiment. Journal of Geophysical Research: Atmospheres, 126(23). https://doi.org/10.1029/2021JD035186

Paul J. DeMott, Benjamin E. Swanson, Jessie M. Creamean, Yutaka Tobo, Thomas C. J. Hill, Kevin R. Barry, Ivo F. Beck, Gabriel P. Frietas, Dominic Heslin-Rees, Christian P. Lackner, Julia Schmale, Radovan Krejci, Paul Zieger, Bart Geerts, Sonia M. Kreidenweis; Ice nucleating particle sources and transports between the Central and Southern Arctic regions

during winter cold air outbreaks. *Elementa: Science of the Anthropocene* 3 January 2025; 13 (1): 00063. doi: https://doi.org/10.1525/elementa.2024.00063

Hill, T. C. J., DeMott, P. J., Tobo, Y., Fröhlich-Nowoisky, J., Moffett, B. F., Franc, G. D., & Kreidenweis, S. M. (2016). Sources of organic ice nucleating particles in soils. Atmospheric Chemistry and Physics, 16(11), 7195–7211. https://doi.org/10.5194/acp-16-7195-2016

Daily, Martin I.; Tarn, Mark D.; Whale, Thomas F. An evaluation of the heat test for the ice-nucleating ability of minerals and biological material Atmospheric Measurement Techniques, Vol. 15, Issue 8 https://doi.org/10.5194/amt-15-2635-2022

Section 3.2: Are there studies about the ice nucleation activity of the discussed bacterial taxas?

Ice nucleation has been attributed primarily to three genera: *Pseudomonas, Pantoea, and Xanthomonas* (Hill et al. 2018). These genera were not associated with our top-20 found during MOSAiC. There are still a lot of unknowns about biological ice nucleation. Even though we have evidence for the INPs being of biological origin, we cannot provide a definite link with the amplicon sequencing information here, and the bacterial INPs will come from a small percentage of the total bacteria. The IN activity could also be attributed to fungi.

Hill, T. C. J., DeMott, P. J., Conen, F., & Möhler, O. (2018). Impacts of Bioaerosols on Atmospheric Ice Nucleation Processes. In A.-M. Delort & P. Amato (Eds.), Microbiology of Aerosols (1st ed., pp. 197–219). John Wiley & Sons.

Section 3.2: How does the seasonal cycle of bioaerosol relate to the Arctic haze phenomena?

We will add: "The seasonal cycle of the Arctic haze corresponded to the occurrence of a diverse population of bioaerosols that was most likely from longer range transport, with a lower population of marine taxa." (Lines 221-223)

Figure 3 and Figure 5: Why do these figures have headers?

Thank you for pointing this out, they are now removed.

Lines 247 – 248: Only when reading the figure caption of Fig. 6 it became clear to me what you mean with the relative percentages of each zonal coverage, I suggest to explain it in more detail in the text.

We have changed the text to closely match the caption:

"Ice is defined as greater than 85% sea ice concentration (SIC), marginal ice zone (MIZ) is 15-85% SIC, ocean is <15% SIC, and land." (Lines 257-259)