Author Response to Referee #1
EGUSPHERE-2026-308

The manuscript presents one-month measurements of the INP concentration, size distribution and chemical species in the Chinese city of Taiyuan. While for days influenced by dust transport an enhanced INP concentration and inas density was observed, pollution episodes did not influence the aerosols' freezing ability substantially. As none of the chemical components correlated with the INP concentration during non-dust days, they concluded that the INP population in these times is composed of an interplay of particles rather than one single source.
Overall, the manuscript is well written and suits the scope of the journal. However, there are some points, listed below, that need clarification and would further improve the quality of the paper. After addressing these comments, I would recommend the manuscript for publication.
Response: We thank the reviewer for the careful reading of our manuscript and for the positive overall assessment. We appreciate the reviewer's concise summary of the main findings and the recognition that the manuscript is generally well written and within the scope of the journal. We have carefully considered all of the comments below and revised the manuscript accordingly. Detailed responses are provided point by point.

General comments

In L.172 you state that the surface area A, used to calculated ns, is obtained from the SMPS measurements. According to L.111 the SMPS data cover the diameter range from 3 nm–453 nm. With that, you leave out the particles larger than 0.5 µm in size, which are thought to be the most active in ice formation and many parameterizations are based on that. Even though the number of particles larger than 0.5 µm in size might be low, the total surface area is strongly affected. I am aware that the conversion from the optical to the aerodynamic diameter may introduce some uncertainty, however, not including these particles in the surface area will increase the uncertainty of ns. I would suggest calculating ns with the combined size distribution of the SMPS and OPC and provide a detailed discussion on the uncertainty of the surface area and with that ns. Furthermore, the discussion around Fig. 2 and the comparison to literature data and parameterizations should be revised.
Response: We thank the reviewer for this important comment. In the actual ns calculation, the total particle surface area A was derived from the combined particle size distributions measured by the SMPS and OPC, rather than from SMPS data alone. Thus, the contribution of particles larger than 0.5 µm was included in the calculation. The sentence stating that "A was calculated based on concurrent SMPS data" was inaccurate and has been revised accordingly. We have revised the manuscript to clarify this point explicitly and to better describe how the merged SMPS–OPC size distribution was used to estimate A for n_s calculation. We have also clarified the uncertainty associated with diameter conversion and surface-area estimation, and revised the relevant text accordingly.

Changes in manuscript:
(1) Section 2.2.1: “The OPC data were combined with the SMPS measurements to construct a merged particle size distribution (SMPS: 3–453 nm; OPC: 0.5–20 μm), which was further used to estimate the total particle surface area for n_s calculation.”
(2) Section 2.2.3: “...and A was calculated from the combined particle size distributions measured by the SMPS and OPC.”
(3) Section 3.3: “The n_s values discussed here were calculated from the merged SMPS–OPC size distribution, thereby accounting for contributions from coarse particles in the surface-area estimate.”

Minor comments

- L.92: Please add the altitude of the measurement site

Response: We have added the approximate ground elevation of the sampling site in the revised manuscript.
Changes in manuscript:
Section 2.1: “The sampling site (37.88°N, 112.55°E; approximately 800 m a.s.l.) is located on the rooftop (~20 m above ground level) of a four-story building at the Taiyuan Municipal Ecology and Environment Bureau.”

- L.102: What is a two-channel sampler? Did you sample 2 filters in parallel with that? And what is your sampling cut-off? Please provide more details on that.

Response: Here, “two-channel sampler” refers to a sampler equipped with two independent parallel filter channels, allowing two 47 mm filters to be mounted and sampled simultaneously. In this study, the sampler was operated without a cyclone or other size-selective inlet; therefore, no specific aerodynamic cut-off was applied, and the collected aerosol can be regarded as approximately total suspended particles (TSP). We have revised the manuscript to clarify these details.
Changes in manuscript:
Section 2.1: “In addition, INP filter samples were collected using a two-channel sampler equipped with two parallel filter channels from 4 December 2023 to 5 January 2024. Polycarbonate filters (47 mm, Nuclepore Track-Etch Membrane, 0.2 μm pore size, Whatman) were used for sampling. The sampler was operated without a size-selective inlet.”

- L.121: Why did you convert everything to the mobility diameter? In the manuscript you don’t pick it up again, so I think you should discuss the conversion of the mobility diameter to the aerodynamic diameter and give an uncertainty for that.

Response: The size distributions were expressed in mobility diameter because the particle surface area used for ns calculation needs to be calculated on the same diameter basis. The SMPS data are given in mobility diameter, whereas the OPC measures optical-equivalent diameter for larger particles. Therefore, the OPC size distribution was converted to mobility diameter before being merged with the SMPS data for surface-area calculation.
The main uncertainty in this conversion comes from the assumptions used in the conversion. In the revised manuscript, we now state that an effective particle density of

1.5 g cm^{-3} and a shape factor of 1 were assumed. Chen et al. (2021) evaluated the effect of particle density and shape factor on ns calculation and showed that changing the particle density from 1.5 to 2.6 g cm^{-3} and the dynamic shape factor from 1.1 to 1.4 can lead to a factor of 1.07–2.36 difference in ns. This result indicates the possible magnitude of uncertainty caused by diameter conversion. For our dataset, an exact uncertainty cannot be assigned because particle refractive index, morphology, and sample-specific effective density were not independently measured. We have clarified these assumptions and the related uncertainty in the revised manuscript.

Changes in manuscript:

Section 2.2.1: "To merge the OPC data with the SMPS measurements and calculate particle surface area on the same diameter basis, the OPC size distribution was converted to mobility diameter (d_m). Estimating d_a from optical-equivalent diameter typically requires knowledge of particle complex refractive index and morphological parameters (e.g., dynamic shape factor) (Peters et al., 2006). Moreover, when converting to dm, we assumed an effective particle density of 1.5 g cm^{-3} and a shape factor of unity. Previous sensitivity calculations showed that changing the particle density from 1.5 to 2.6 g cm^{-3} and the dynamic shape factor from 1.1 to 1.4 can lead to a factor of 1.07–2.36 difference in n_s (Chen et al., 2021). This suggests that diameter conversion may introduce an uncertainty of approximately a factor of 2 in n_s, particularly in the coarse-mode size range (Huang et al., 2021). A more exact uncertainty could not be assigned because particle refractive index, morphology, and particle-specific effective density were not independently measured."

- L.122: Here you should give the value of the uncertainty. I think this is an important addition also for the discussion of ns, which should include the larger particles (see my comment in the general comments section)

Response: The uncertainty of ns cannot be represented by a single well-constrained numerical value from the present measurements. This is because n_s depends on both N_{INP} and the particle surface area concentration used for normalization. The uncertainty in N_{INP} mainly arises from the statistical limitation of the droplet-freezing experiment, as described in Sect. 2.2.3. The uncertainty in the particle surface area concentration is mainly associated with the merged SMPS–OPC size distribution, especially the conversion of OPC optical-equivalent diameters in the coarse-mode range. This conversion requires assumptions regarding particle density and shape factor, while particle-specific refractive index, morphology, and effective density were not independently measured. Therefore, we did not assign an unsupported single numerical uncertainty to n_s, but clarified the main uncertainty sources in the revised manuscript. The contribution of coarse-mode particles was included in the SMPS–OPC merged particle surface area used for ns calculation, as also clarified in the response to the general comment above.

Changes in manuscript:

Section 2.2.3: "For each aerosol sample, the parameters ($f_{ice}(T)$, $K(T)$, $N_{INP}(T)$, $n_s(T)$, and the confidence intervals for $N_{INP}(T)$) were calculated individually. The $f_{ice}(T)$ was derived from cold-stage measurements, V_{air} was obtained from recorded sampling volumes, and A was calculated from the standard-condition combined particle size

distributions measured by the SMPS and OPC. The uncertainty in ns arises from both the statistical uncertainty in N_{INP} and the uncertainty in the particle surface area concentration used for normalization. The latter is mainly associated with the SMPS–OPC merging and diameter conversion in the coarse-mode range, as discussed in Section 2.2.1."

- L.153: Were also the aerosol data converted to standard conditions?

Response: In the original calculation, the INP filter-sampling volume from the two-channel sampler used to derive N_{INP} had been converted to standard conditions (0 °C, 1013 hPa). Following the reviewer's comment, we have also converted the particle number size distributions to the same standard-condition air-volume basis using concurrent temperature and pressure data. The particle number and surface area concentrations derived from the size distributions were then recalculated and used to update the corresponding n_s values and related figure data.

This correction caused only minor quantitative changes. For example, the daily correction factor for the particle surface area concentration ranged from 0.981 to 1.142, with a mean value of 1.079 during the INP observation period. The recalculated n_s values were slightly lower on average, but the main patterns and conclusions were unchanged.

Changes in manuscript:

Section 2.2.3: "For $n_s(T)$ calculation, the merged SMPS–OPC particle number size distributions were converted to the same standard-condition air-volume basis as N_{INP} (0 °C, 1013 hPa) using concurrent temperature and pressure data. The particle surface area was then estimated from the converted size distributions expressed in mobility diameter."

- L.178: Please specify why you chose 850 m a.s.l.; is it the height of the station?

Response: The arrival height of 850 m a.s.l. was chosen to approximately represent the actual sampling inlet height, considering that the ground elevation of the sampling site is about 800 m a.s.l. and the sampling inlet was located on the rooftop at about 20 m above ground level. We have clarified this in the revised manuscript.

Changes in manuscript:

Section 2.2.4: "Trajectories were calculated with a duration of 72 h and an interval of 6 h between each trajectory, arriving at an altitude of 850 m above sea level (a.s.l.), which approximately represents the actual sampling inlet height, considering a ground elevation of about 800 m a.s.l. and a rooftop sampling height of about 20 m above ground level."

- L.206: You discuss here the INP concentration at a temperature of -15 °C. However, looking into Fig. 1a, it is not clear which of the temperature ranges you mean (-12.5 °C--15 °C or -15 °C to 17.5 °C). Please clarify it in the text.

Response: Here, the INP concentration at −15 °C refers to the cumulative $N_{INP}(T)$ evaluated at T = −15 °C, i.e., the total INP concentration active at and above this temperature, rather than to a specific temperature interval shown in Fig. 1a. We have clarified this in the revised manuscript.

Changes in manuscript:

Section 3.1: “At and above −15 °C, the cumulative $N_{INP}(T)$, representing the total INP concentration active at and above this temperature, ranged from 10^{-2} to 10^{1} L^{-1} with a campaign mean of 1.75 L^{-1}.”

• L.207: Do you refer to the ns values seen in Fig. 3? Either add the reference to the figure or add the ns values in Fig. 1.

Response: The n_s values referred to here are those shown later in Fig. 3. To avoid overcrowding Fig. 1, we have added an explicit reference to Fig. 3 in the revised text rather than adding n_s values to Fig. 1.

Changes in manuscript:

Section 3.1: “Correspondingly, the n_s values at and above −15 °C (see Fig. 3) spanned 10^{5} to 10^{7} m^{-2}, with a campaign mean of 3.42×10^{6} m^{-2}.”

• Fig.1a: The color of the bars of the INP concentration seems to change when you mark the special periods such as the dust transport. For more clarity, please make sure that the shaded areas are in the back and do not change the color the other markers.

Response: We have revised Fig. 1a by replacing the original shading with dashed boundary lines and arrow annotations to indicate the special periods. This avoids interference with the original colors of the INP bars and improves the clarity of the figure.

Changes in manuscript:

(1) Section 3.1: “Several distinct events can be identified throughout the campaign, as indicated in Fig. 1 by dashed boundary lines and colored arrows. The first event (5–9 December, marked by the orange arrow in Fig. 1a) was characterized by a sharp increase in coarse-mode (here defined as particles with aerodynamic diameter >1 μm, $N_{>1\mu m}$) particle concentrations (Figs. 1b, S1b, and S2).”

(2) Section 3.1: “Other episodes (13–14, 18, and 28–30 December, marked by the gray arrows in Fig. 1a) were characterized by simultaneous increases in sulfate, nitrate, ammonium, and organic carbon, accompanied by elevated both $PM_{2.5}$ and PM_{10} mass (Fig. 1c and Fig. 1d).”

(3) Section 3.3: “During the desert dust event (5–9 December; marked by the orange arrow and dashed boundary lines in Fig. 1a), both N_{INP} and ns increased markedly.”

(4) Figure 1 caption added: “Special periods are indicated by dashed boundary lines across all panels and colored arrows at the top of panel (a): the orange arrow denotes the desert dust period, the gray arrows denote pollution periods, and the red arrow denotes the fireworks event.”

• Fig. 1a: The gray triangles of the DeMott et al., 2015 parameterization should be removed here. You can add them to Fig. 2, where you anyways discuss some INP parameterizations.

Response: We understand the reviewer’s concern regarding figure clarity. However, we prefer to retain the DeMott et al. (2015) parameterization in Fig. 1a, because its purpose here is not primarily to provide a general parameterization comparison, but to show the day-to-day difference between the D15-predicted INP concentrations and the observed values during different periods of the campaign. Since the D15 values were calculated using the corresponding daily coarse-particle number concentrations, placing them in

the time-series panel allows a direct temporal comparison with the observations. By contrast, Fig. 2 is mainly intended for temperature-dependent comparison with previous studies and reference parameterizations, and moving D15 there would weaken its value as a temporal diagnostic. To improve readability, we have revised Fig. 1a and clarified the role of D15 in both the figure caption and the main text.

Changes in manuscript:

(1) Figure 1a has been revised to improve clarity while retaining the D15(−20 °C) time-series comparison.

(2) Figure 1 caption: "In panel (a), gray triangles (D15(−20 °C)) represent values calculated using the NINP parameterization scheme proposed by DeMott et al. (2015), shown here to compare the day-to-day temporal variation between parameterized and observed INP concentrations."

(3) Section 3.3: "Figure 1a also compares the measurements with the DeMott et al. (2015) parameterization (D15), allowing a direct day-to-day comparison between the parameterized and observed INP concentrations during different periods of the campaign."

- L.236: Cu and Sr are not shown in Fig. 1c or 1d.

Response: These species were measured and showed concurrent enhancements during the fireworks event, but they were not retained in the final version of Fig. 1 in order to avoid overloading the panel. The text was not updated accordingly, which caused the inconsistency. We have now revised the text to match the current figure.

Changes in manuscript:

Section 3.1: "Around 2 January 2024 (marked by the red arrow in Fig. 1a), a short-lived pollution event occurred, accompanied by sharp increases in PM mass and concurrent peaks in K, OC, and EC (Figs. 1c and 1d), which are consistent with firework emissions during New Year celebrations."

- Fig. 2: Your freezing spectra of the dust episode have a very interesting profile, which is very characteristic of biological aerosol particles and not in the first place of dust. Hu et al., 2023 observed a similar INP concentration in Beijing in spring during dust transport. They performed a heat treatment on the samples and concluded that there might be some mixing of the dust aerosol with more heat sensitive, potentially biological, particles. Did you also perform a heat treatment to your samples? I think the discussion you provide in L.310 ff should be provided already here, with reference to the above-mentioned paper.

Response: We did not perform heat-treatment experiments on these samples and therefore cannot directly evaluate the contribution of heat-sensitive biological components in this study. However, the revised manuscript now acknowledges this possibility earlier in the discussion associated with Fig. 2. Previous heat-treatment results during East Asian dust events showed that heat-sensitive INPs made substantial contributions at relatively warm temperatures (Chen et al., 2021), and Hu et al. (2023) reported similar behavior during spring dust transport in Beijing. We now state that the enhanced warm-temperature activity during the Taiyuan dust episode may reflect the combined influence of transported mineral dust and potentially co-transported heat-sensitive components, although such a contribution can only be inferred and cannot be

directly assessed in the absence of heat-treatment analysis in this study.

Changes in manuscript:

Section 3.2: "However, the enhanced warm-temperature INP activity during this episode may not be fully attributable to mineral dust alone. During East Asian dust events, Chen et al. (2021) showed that heat-sensitive INPs made substantial contributions at relatively warm temperatures. Similarly, Hu et al. (2023) reported enhanced warm-temperature INP activity during spring dust transport in Beijing and suggested, based on heat-treatment analysis, that transported dust particles may be mixed with heat-sensitive, potentially biological components. Together, these studies support the possibility of similar heat-sensitive contributions during the Taiyuan dust episode. In the present study, however, no heat-treatment analysis was performed; therefore, such a contribution can only be inferred and cannot be directly assessed."

- L.274: should be orange instead of light gray

Response: The corresponding text has been revised from "light gray" to "orange".

- L.278 ff: DeMott et al., 2015 is a parameterization made for desert dust aerosol. While for the dust episode it is a valid choice, it is expected that for the remaining measurements it might not provide reasonable results. Please specify this in the text.

Response: We agree that the DeMott et al. (2015) parameterization was developed for desert dust aerosol and is therefore most appropriate for interpreting the dust episode in this study. For the non-desert-dust periods, we do not use D15 as a general predictor, but rather as a dust-based reference to show how the observed INP concentrations deviate from desert-dust-dominated behavior. We have clarified this point in the revised manuscript and now explicitly state that the interpretation of D15 during non-desert-dust periods should be made with caution.

Changes in manuscript:

Section 3.3: "Figure 1a also compares the measurements with the DeMott et al. (2015) parameterization (D15), which links INP concentrations to the number concentration of particles larger than 0.5 μm and was originally developed for desert dust aerosol. Accordingly, it is most appropriate for the dust episode in this study, whereas for the remaining periods it is shown mainly as a dust-based reference and should be interpreted with caution."

- L.340: Did you also check the same correlations for other temperatures?

Response: We have additionally examined the correlations between the daily mean PMF-resolved source contributions and N_{INP} at −10, −12.5, −15, and −17.5 °C, in addition to −20 °C. Values indicating complete freezing before the corresponding temperature were excluded from the correlation analysis. As shown in the newly added Table S2, none of the PMF-resolved factors showed statistically significant correlations with N_{INP} at any examined temperature ($p > 0.05$). Therefore, the main interpretation is not sensitive to the selected temperature.

Changes in manuscript:

Section 3.4: "Similar analyses were also conducted at −10, −12.5, −15, and −17.5 °C (Table S2). No statistically significant correlations were found between N_{INP} and any PMF-resolved factor at the examined temperatures ($p > 0.05$), indicating that this result was not specific to the choice of −20 °C."

• Conclusions: When you discuss your findings during the dust transport episode, you should mention that potential aging processes do not suppress the INP efficiency. Next to that, you should mention again the potential mixing with biogenic particles. Since they are very ice active, it could be that you see in your samples primarily the biogenic particles freezing rather than the dust particles.

Response: In the revised manuscript, we now state that comparison with previously reported dust parameterizations indicates that transported desert dust retained strong ice-nucleating activity during the dust transport episode. We also reiterate that the enhanced warm-temperature activity may reflect not only transported mineral dust, but also the possible contribution of co-transported biological components. However, because no heat-treatment analysis was performed in this study, this remains a plausible interpretation rather than a direct confirmation.

Changes in manuscript:

Conclusions: "Comparison with previously reported dust parameterizations indicates that the transported desert dust retained strong ice-nucleating activity during the dust transport episode. The enhanced warm-temperature activity may also reflect the possible contribution of co-transported biological components, although this cannot be directly verified in the absence of heat-treatment analysis."

References

Hu, Y., Tian, P., Huang, M., Bi, K., Schneider, J., Umo, N. S., Ullmerich, N., Höhler, K., Jing, X., Xue, H., Ding, D., Liu, Y., Leisner, T., and Möhler, O.: Characteristics of ice-nucleating particles in Beijing during spring: A comparison study of measurements between the suburban and a nearby mountain area, Atmospheric Environment, 293, 119451, https://doi.org/10.1016/j.atmosenv.2022.119451, 2023.

Chen, J., Wu, Z., Chen, J., Reicher, N., Fang, X., Rudich, Y., and Hu, M.: Size-resolved atmospheric ice-nucleating particles during East Asian dust events, Atmospheric Chemistry and Physics, 21, 3491–3506, https://doi.org/10.5194/acp-21-3491-2021, 2021.