Black colour is used for Referee statements

Blue colour is used for response to comments

Maroon colour is used to quote text in manuscript

Referee: 2

Peer Review Report

Manuscript title: Frequent new particle formation events in the Indo-Gangetic Plain occur under reduced condensation sink but are obscured by air mass heterogeneity

Journal: Atmospheric Chemistry and Physics

Manuscript number: egusphere-2026-2212

Summary

This manuscript presents an observational study investigating new particle formation (NPF) at a suburban site in the Indo-Gangetic Plain (IGP) between May and December 2023. By combining measurements from a Scanning Mobility Particle Sizer (SMPS) with a Neutral Cluster and Air Ion Spectrometer (NAIS), the authors extend their aerosol characterization down to the sub-10 nm size range, for which observational data in this region is limited. This combined instrument approach allows the authors to evaluate particle size distributions ranging from 2.5 to 570 nm to characterise seasonal and diurnal variability in aerosol populations.

A main focus of the study is the comparative evaluation of three NPF event classification schemes: Dal Maso et al. (2005), Dada et al. (2018), and Aliaga et al. (2023). The Dal Maso et al. method relies on visual inspection, the automated Dada et al. method compares 2–4 nm ion bursts with larger particle concentrations to distinguish regional from transported events, and the statistical Aliaga et al. method groups events into activity percentiles based on 2.5–5 nm concentration changes. All three methods show general qualitative agreement but quantitative discrepancies. These discrepancies are attributed to the complex interplay of meteorological variability, high background aerosol loading, and overlapping anthropogenic sources that mask genuine nucleation signals.

The study also quantifies important NPF parameters, finding that particle growth rates (GR) are elevated compared to those in cleaner environments, indicating enhanced growth. Condensation sink (CS) on event days was roughly half that of non-event days. While higher than in clean environments, the CS remained below the suppression thresholds typical of heavily polluted regions, positioning this suburban site within an intermediate-pollution regime. Ultimately, the manuscript underscores the critical need for refined NPF classification methodologies specifically tailored for multi-source, high condensation sink environments.

General Impressions

Combining SMPS measurements with NAIS measurements to observe particle size distributions within the IGP is worthwhile and expands our scientific understanding of particle formation at different global sites. Evaluating and comparing different classification methods for particle formation events is also important, as a rigorous, consistent, and accurate method is necessary. Although the manuscript stops short of proposing a novel classification solution tailored for such environments, the insights it provides into the limitations of current metrics are inherently valuable to the aerosol physics community.

Overall, I find this manuscript a valuable contribution. However, currently, the manuscript is marred by confusion about the coverage of the observed data. While Figure S6 in the supplementary material provides a timeline of the NAIS and SMPS overlap, this figure is not referenced in the main text. Consequently, it remains unclear during the reading of the main text how many days actually had proper instrumental overlap, and the implications of these severe data gaps are never discussed. This issue is further explained in my major comment and should be resolved before publication. I, therefore, recommend publication with minor revisions.

We thank Referee 2 for the constructive assessment and for recognizing the value of the combined NAIS and SMPS observations from the Indo-Gangetic Plain. We agree that the earlier manuscript needed a clearer presentation of the data coverage and analysis-specific sample size details. In the revised manuscript, we have explicitly separated the full May–December 2023 campaign period, the 108 valid NAIS classification days, the smaller concurrent NAIS–SMPS subset used for sink calculations, and the three formation-rate case-study days. We have also cited the data-availability calendar in the main text and revised the relevant Methods, Results, and Discussion sections accordingly.

Major Comments

1. Inconsistent and Unclear Data Coverage: The manuscript states that observations were conducted from May to December 2023. Assuming continuous operation, this period spans approximately 214 days. However, Section 3.2.1 abruptly introduces a study period of only 108 days. While Figure S6 in the supplementary material visualizes the NAIS and SMPS data availability across this period, this figure is never referenced or discussed in the main text, leaving the reader without a clear accounting of the operational gaps.

More concerning is a brief statement at the end of Section 3.2.2: "Also it is to be noted that only 11 NPF days where overlapping SMPS and NAIS measurement days were available". Because combining NAIS and SMPS data is a central methodological feature of this study, this severe limitation must be featured prominently at the beginning of the methodology or results section, rather than as a concluding side note. Furthermore, the implications of this statement are confusing. According to the Dal Maso classification in Section 3.2.1, there were 50 event days (Classes I and II). Even when referencing Figure S6, does this mean that NAIS and SMPS measurements overlap for less than 25% of the identified event days? If so, what is the reason for this lack of overlap over the studied period?

Continuing, the text states that "after filtering only 3 such days were possible where we could reliably calculate the growth rate". Deriving growth rates (and subsequently, particle formation rates, which depend on these growth rates) from a sample size of N = 3 is insufficient to establish statistically robust conclusions or regional averages. The results derived from these 3 days must be explicitly framed as isolated case studies rather than representative climatological values.

The authors must explicitly reference and discuss Figure S6 in the Methods section to clearly document the exact measurement coverage (NAIS, SMPS, and meteorological variables) over the May–December 2023 period. Additionally, for all calculated properties (growth rate, condensation sink, and formation rates), the exact number of days used for the calculations must be stated upfront in the relevant subsections. The authors must also include a robust discussion on how this limited data coverage, and any potential seasonal biases within the available data, impacts the statistical significance and general applicability of their findings.

Response: We agree that the measurement coverage needed to be stated more clearly and earlier in the manuscript. In the revised manuscript, Sect. 2.3 now gives the analysis-specific data coverage before any derived NPF parameters are discussed. The overall measurement campaign covered May–December 2023, but the NAIS-based classification was performed using 108 valid NAIS days after filtering for instrument interruptions, missing data, precipitation-affected ion measurements, and gaps during the daytime growth/classification window.

We now explicitly state that the concurrent NAIS–SMPS subset is much smaller and is used only for quantities requiring the larger particle-size distribution. There are 26 concurrent days in which 11 days were classified as NAIS event days and 15 as NAIS non-event days. Of the 11 concurrent NAIS-event days, two days (6 September and 16 October 2023) were flagged as ambiguous/disagreement cases because the SMPS-size distribution did not support a clean event-day interpretation; these two days were therefore not included in the strict event/non-event CS comparison. So, 9 event days and 15 non-event days were used for the strict event/non-event condensation-sink comparison. The daily CS values were summarised over 06:00–12:00 LT using the merged NAIS–SMPS PNSD.

We also clarify that the "three days" limitation applies to particle formation-rate (J) case-study calculations, not to the full growth-rate (GR) analysis. GR was estimated from manually screened NAIS event days selected from the modified Dal Maso et al. (2005) Class I and Class II events. This procedure yielded 17 NAIS event days suitable for at least one GR estimate. The successful-fit counts are now reported explicitly: 6 and 5 successful fits for the 3-7 nm range using the appearance-time and Gaussian/mode-peak methods, respectively, and 12 and 15 successful fits for the 7-20 nm range. The three J case-study days were obtained by intersecting the days with concurrent NAIS-SMPS measurements with the event days for which a reliable GR could be estimated and all J terms could be calculated. Thus, J was not calculated for all 11 concurrent NAIS event days, because formation-rate calculation also required reliable dN/dt, CoagS from the merged NAIS-SMPS PNSD, a usable GR, and the growth-out-of-range correction. Only three event days satisfied all these requirements, and these are therefore presented as case-study estimates rather than seasonal or campaign-wide averages. Thus, GR statistics are presented as manually screened event-wise estimates, whereas J values are restricted to three case-study days with concurrent NAIS-SMPS data and all required terms available.

Text revised/added in the manuscript: [Sect. 2.3, p. 6, line 203-209]

Data coverage for the different instruments and derived quantities is summarised in Fig. S1. Although the overall measurement period extended from May to December 2023, the number of valid days available for individual analyses differed because of instrument interruptions, missing data periods, precipitation-affected ion measurements, and gaps during the daytime growth window used for event classification. The NAIS-based NPF classification was performed using 108 valid NAIS days. SMPS measurements usable for the concurrent NAIS-SMPS analysis were available for a limited subset of the campaign (26 days), mainly during August-November 2023.

Text revised/added in the manuscript: [Sect. 2.3, p. 8 line 294 to p. 9 line 302]

For GR estimation, the modified Dal Maso et al. (2005) classification was used to identify candidate event days... This procedure yielded 17 NAIS event days suitable for at least one GR estimate.

Text revised/added in the manuscript: [Sect. 2.3, p. 9, line 309-318]

For the event/non-event CS comparison, daily CS values were summarised as the median CS during 06:00-12:00 LT. This morning window was selected to represent the pre-onset, onset, and early-growth period of NPF while avoiding later afternoon boundary-layer accumulation and local emission effects. Condensation sinks were calculated only for days with concurrent NAIS and SMPS data (9 event days and 15 non-event days), because particles outside the NAIS size range contribute substantially to these sinks. For CS calculations, NAIS particle data were used up to 20 nm and SMPS data above 20 nm, producing a merged PNSD of approximately 2.5-570 nm for concurrent-instrument days.

Text revised/added in the manuscript: [Sect. 2.3, p. 9 lines 321-324 ; p. 10 lines 336-338]

These calculations were performed only for three case-study event days with concurrent NAIS and SMPS data and sufficient data quality for dN/dt, CoagS, and the growth-out-of-range term... Formation rates were therefore calculated only for the smaller case-study subset of event days for which all required terms (CS from SMPS-NAIS data, GR from NAIS data) could be determined reliably.

Minor Comments

• In addition to Figure S6 (noted in the major comment), Figures S2, S3, and S4 are provided in the supplementary document but are never referenced in the main text. Please ensure that all supplementary materials are explicitly cited in the appropriate sections of the manuscript so that readers are directed to this supporting information.

Response:

Corrected. The data-availability calendar referred to by the reviewer has since been renumbered and is now presented as Fig. S1. Fig. S1, S2, S3, S4, and S6 are now cited in the main manuscript where they support the classification, data-availability, and class-composite discussions.

Fig. S1 [Sect. 2.3, p. 6 line 203], **Fig. S2** [Sect. 2.3, p. 6 line 210], **Fig. S3** [Sect. 3.2.1, p. 14 line 453], **Fig. S4** [Sect. 3.2.1, p. 15 line 479], **Fig. S5** [Sect. 3.2.1, p. 17 line 528], **Fig. S6** [Sect. 3.2.2, p. 19 line 567], **Fig. S7** [Sect. 3.2.2, p. 19 line 568].

• The manuscript contains several sentences that are grammatically incorrect, awkwardly phrased, or confusing, which occasionally obscures the scientific meaning. A non-exhaustive list of examples is provided below. I strongly recommend a thorough proofreading of the entire manuscript prior to publication.

We have proofread the manuscript and revised grammatically incorrect or unclear sentences throughout. This included correcting singular/plural agreement, missing articles, subject–verb agreement, informal phrasing, and repeated wording. We also checked the reference list and removed duplicate entries, including the duplicate Aalto et al. (2001) citation.

– Page 3, line 77: “In the overall aerosol loading, NPF contribution varies place to place and time to time but no doubt that it makes a significant part of that” Please clarify what ‘that’ refers to in this context and rephrase for formal tone.

Text revised/added in the manuscript: [Sect. 1, p. 2 lines 47-49]

Atmospheric observations and model studies show that NPF followed by growth can contribute substantially to atmospheric particle number concentrations, while its contribution to cloud condensation nuclei (CCN) depends on whether newly formed particles grow to CCN-relevant sizes.

– Page 3, line 79: “we need to characterise them with getting their frequency, growth rate, and formation rate.” Consider revising to “...by determining their frequency...”

Not needed due to total rephrasing.

– Page 3, line 94: “Some Industrial chimneys also exist on the other side of the cross highways.” Please correct the capitalization of the common noun (‘industrial’) and consider replacing ‘cross highways’ with a more precise term, such as ‘intersecting highways’.

Text revised/added in the manuscript: [Sect. 2.1, p. 3 lines 94]

Industrial chimneys are also located beyond the intersecting highways.

– Page 6, line 183: “Unfavourable meteorological conditions often exacerbate pollutant accumulation...” Please clarify what constitutes an “unfavourable” condition in this context (e.g., conditions unfavourable for atmospheric dispersion, such as low wind speeds or temperature inversions?).

Text revised/added in the manuscript: [Sect. 2.3, p. 7 lines 220-223]

Conditions unfavourable for atmospheric dispersion, such as low wind speeds, shallow boundary-layer heights, and stagnant high-pressure periods, often enhance pollutant accumulation, leading to exceptionally high $PM_{2.5}$ concentrations.

– Page 7, line 194: “for days when event occur but visually not as well standard as Ia)” The phrasing here is awkward; please revise for grammatical correctness and clarity.

Text revised/added in the manuscript: [Sect. 2.3, p. 7 lines 233-235]

Class Ia denotes well-defined events, Class Ib denotes events that are visible but less clear than Class Ia, and Class II denotes less distinct events with weaker growth signatures.

– Page 13, line 374: “and rest 58 non-events days” Revise for grammatical correctness (e.g., “and the remaining 58 non-event days”).

Text revised/added in the manuscript: [Sect. 3.2.1, p. 14 lines 449-451]

Using the Dal Maso et al. (2005) method, we identify a total of 10 Class I events, 40 Class II events, and the remaining 58 non-event days over the 108-day study period.

– Page 21, line 545: "Typical day time CS values observed in Delhi has been reported more than ∼0.06 s−1 to sustain NPF events (Ali et al., 2025)." This sentence is confusing as it currently implies that the CS must be greater than ∼0.06 s−1 to sustain NPF, which contradicts the physical mechanisms discussed. Please rephrase to clarify the threshold.

Text revised/added in the manuscript: [Sect. 3.2.2, p. 22 lines 620-622]

Previous observations in Delhi show that NPF events are typically observed when CS remains below ~0.06 s^{-1}, despite a wider observed CS range, indicating that sufficiently reduced sink conditions are needed for particle formation and sustained growth (Ali et al., 2025).

– Page 23, line 593: "This observed decoupling between ion and nucleation-mode particle dynamics signals towards the fact that controlling influence of precursor vapor abundance and the condensation sink are play a more important role in controlling particle survival and growth." This sentence contains grammatical errors ("are play a more important role") and is difficult to parse. Please revise.

Text revised/added in the manuscript: [Sect. 3.2.2, p. 22 lines 655-656]

The observed decoupling between ion and nucleation-mode particle dynamics indicates that precursor vapour abundance and the condensation sink play more important roles in controlling particle survival and growth.

– Page 28, line 700: "The relatively high-end threshold observed here suggests the strong sources of vapours that form clusters and grow them fast enough for maintaining high enough survival probability." The current phrasing incorrectly implies that the sources themselves grow the clusters. Consider revising to: "...suggests strong sources of vapours that form clusters and enable rapid growth, maintaining a high enough survival probability."

Not needed due to total rephrasing.

• The column headers in Table 1 currently display only the units (e.g., ($cm^{-3}s^{-1}$)) without specifying the corresponding physical parameters or variables (e.g., J3, J7). Please update the headers to indicate both the parameter and its unit.

Response:

Table 1 now includes parameter names and units in the header row, not units alone.

Updated: Table 1.

• Page 9, line 259: "We have gone through days and further filtered days where NPF signals were less affected by other factors." This statement is methodologically vague. Please explicitly define what these "other factors" are and outline the specific criteria used for this filtering.

Response:

We have revised the GR methodology to explicitly state which factors were considered during manual filtering and how the retained GR cases were selected.

Text revised/added in the manuscript: [Sect. 2.3, p. 8 lines 294-302]

For GR estimation, the modified Dal Maso et al. (2005) classification was used to identify candidate event days. Class I and Class II days were considered because both categories can contain visually traceable growth features. Each candidate event day was then inspected individually. The nominal 3–7 nm and 7–20 nm intervals were used as initial search ranges, but the full interval was not imposed if part of the range was affected by noise, weak mode separation, plume-like variability, or discontinuous concentration enhancements. Instead, different contiguous sub-ranges and fitting windows within the nominal intervals were tested, and GR was calculated only for the portion that showed a coherent diameter–time growth pattern representative of NPF. Days or size intervals dominated by short-lived bursts or pseudo-growth signals were excluded from the GR statistics. This procedure yielded 17 NAIS event days suitable for at least one GR estimate.

• Page 9, line 269: "The coagulation sink was calculated using the particle size distribution following standard coagulation theory" Please provide an appropriate citation for the standard coagulation theory referenced here

Response:

We have added citations for the coagulation-sink calculation.

Text revised/added in the manuscript: [Sect. 2.3, p. 9-10 lines 230-332]

The coagulation sink was calculated using standard coagulation theory for interactions between newly formed particles and the background aerosol population (Kulmala et al., 2012; Lehtinen et al., 2007).

• Page 9, lines 261–275: The text details the calculation of the particle formation rate at 3 nm (J3). However, at the very end of the section (line 274), the calculation of J7 is introduced abruptly. I recommend stating upfront that formation rates were determined for both sizes, and clarifying that the equation provided for J3 serves as representative for both calculations.

Response:

We have revised the text to state upfront that formation rates were calculated for both 3 nm and 7 nm, and that the J3 equation is shown as the representative formulation.

Text revised/added in the manuscript: [Sect. 2.3, p. 9 lines 319-321]

The particle formation rate (J) represents the rate at which new particles are formed at a given size and is expressed in cm^{-3} s^{-1}. Formation rates were determined for both 3 nm (J3) and 7 nm (J7), with the J3 equation shown as the representative formulation.

• The manuscript notes that both the Dal Maso et al. and Dada et al. classification methods were modified to mitigate noise in the dataset. While adapting these methods is understandable, restricting the particle growth criterion in the Dada et al. method from the standard 7–25 nm down to 7–12 nm alters the metric being evaluated. Please include 3a brief discussion addressing how these site-specific adaptations impact the comparability of the reported results with other global studies that utilized the standard size bounds.

Response:

– Modification of the Dada et al. size range:

We agree that restricting the Dada et al. particle-growth criterion from 7–25 nm to 7–12 nm changes the metric and affects direct comparability with studies using the standard Dada et al. bounds. We have added this limitation explicitly in the Methods.

Text revised/added in the manuscript: [Sect. 2.3, p. 7 line 255 to p. 8 line 260]

Using monthly mean particle number concentrations above 12 nm, we observed a substantial contribution from background aerosol loading and instrument noise, particularly during the winter months, making it difficult to isolate the NPF growth signal in the full 7–25 nm range prescribed by Dada et al. (2018). Therefore, we restricted the particle-growth criterion to the 7–12 nm range. This site-specific adaptation improves robustness for the present high-background dataset, but it also means that the resulting classes are not directly equivalent to studies applying the standard 7–25 nm Dada et al. bounds.

• The manuscript contains a number of redundant statements that disrupt the narrative flow. A few examples are provided below. I encourage the authors to thoroughly review the text and streamline these repetitions to improve overall conciseness and readability.

We have reviewed the manuscript for repeated statements and streamlined the relevant sections.

– Page 10, lines 291 and 295: The text states, Total particle concentrations in Fig. 2(a) shows clear daytime enhancements during May-June" and shortly thereafter repeats, During the warmer months (May-June), total particle concentrations show pronounced daytime enhancements". Please consolidate these discussions.

For the repeated Fig. 2 description, the revised text now consolidates the discussion of May–June daytime enhancements and seasonal weakening:

Text revised/added in the manuscript: [Sect. 3.1, p. 10, lines 341-344]

NAIS-measured particle concentrations in Fig. 2(a) show clear daytime enhancements during May–June, while these features become more episodic and delayed during August–September. In contrast, October–December exhibits weak and poorly structured diurnal variability, with no clearly defined growth patterns.

– Section 3.2 Introduction: The introductory paragraph of this section (lines 365– 371) largely reiterates site description and methodological context already established in the Methods section. Consider removing this redundancy or integrating it into the Methods section.

We also shortened the introductory part of Sect. 3.2 so that it does not repeat the full site description and methodological context already provided in the Methods.

• While the manuscript predominantly uses British English spelling (e.g., vapour), instances of American English spelling (e.g., minimizing) occasionally appear. Please ensure consistent spelling conventions are applied throughout the text.

We checked and harmonised spelling conventions throughout the revised manuscript.

Summary of marked-manuscript changes

In addition to the text changes listed, the following figures and Table 1 were revised: Fig. 2 (narrowed ion colour scale for panel balance), Fig. 6 (layout corrected for readability), Fig. 9 and Table 1 (condensation-sink values recalculated following the corrected equation), Fig. 10 (timestamp synchronisation corrected), and Fig. 11 (combined with the former Fig. 12 into a single figure with a shared time axis). In the Supplement, figures have been reordered for a clearer sequence, and two new figures have been added: Fig. S7 (event-wise growth-rate fitting diagnostics for the 17 retained GR event days) and Fig. S8 (bootstrap analysis of the event/non-event condensation-sink contrast).

Closing response

We again thank the referees for their constructive comments. The revised manuscript is now more explicit about measurement coverage, the analysis-specific subsets, and the limitations of interpreting derived quantities under limited concurrent NAIS-SMPS availability. We believe these changes make the manuscript clearer, more transparent, and better aligned with the strength of the observations.

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