



The representativeness of observed Δt in calculating formation and growth rates of newly formed atmospheric particles – hypothesis and examination

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Abstract. New particle formation (NPF) is commonly characterized by particle formation rates (FR) and growth rates (GR) derived from fixed-site Eulerian observations. However, particles detected at different times in Eulerian observations do not necessarily represent the evolution of the same air parcel, so the observational time intervals used to derive FR and GR may differ from the corresponding in-situ formation and growth timescales. Here, we examine the representativeness of the observational time interval ($\Delta t_{\text{observe}}$) in the calculation and interpretation of FR and GR using synchronous high-time-resolution measurements from multiple particle instruments in a semi-enclosed indoor environment and ambient air in southeastern Hainan, China. Nine short-term NPF cases were analyzed to determine the observational intervals associated with particle number increase and modal-size evolution. The results show that substantial increases in newly formed particle number concentration and particle growth to tens of nanometers can occur within several to tens of minutes, and that the derived FR of $2.7\text{--}21\text{ cm}^{-3}\text{ s}^{-1}$ and GR of $22\text{--}186\text{ nm h}^{-1}$ were highly sensitive to the selected $\Delta t_{\text{observe}}$. Comparison of the FR-NM1NP (net maximum increase in the nucleation-mode particle number concentration) and GR- D_{pgmax} (maximum geometric median diameter of the grown new particles) relationships between the NPF events in this study and previously reported regional NPF events further revealed substantially lower slopes (by approximately 1–2 orders of magnitude) for events characterized by longer $\Delta t_{\text{observe}}$, suggesting that such intervals may not adequately represent the true formation and growth timescales of newly formed particles.

1 Introduction

New particle formation (NPF) is a major source of explosive increases in atmospheric particle number concentrations and has been investigated in a wide range of environments (Chu et al., 2019; Dal Maso et al., 2005; Kerminen et al., 2018; Kirkby et al., 2016; Kulmala et al., 2004; Merikanto et al., 2009). Over the past few decades, Class I events with characteristic “banana-shaped” patterns, as defined in the classic NPF classification proposed by Dal Maso et al. (2005), have received extensive



attention because their apparently continuous growth patterns are commonly considered suitable for quantifying key parameters such as particle formation and growth rates (Dal Maso et al., 2005; Lehtipalo et al., 2025). In contrast, Class II and undefined events, which exhibit interrupted growth, sudden bursts, or discontinuities in their size distributions, are often excluded from statistical analyses because they are more difficult to quantify precisely. As reviewed by Kulmala et al. (2004) and Chu et al. (2019), NPF events have mainly been observed at fixed sites and are therefore conventionally treated as Eulerian observations. A smaller number of studies have used instruments deployed on moving platforms, such as road vehicles, ships, and aircraft (Thompson et al., 2022; Zhu et al., 2019). These observations should still be regarded as Eulerian in a broad sense, because the platforms almost never move at the same speed and in the same direction as the ambient airflow. Strictly speaking, particles detected at different times in Eulerian observations cannot be assumed a priori to represent the same evolving air parcel. By contrast, only true Lagrangian observations, in which the instruments move concurrently with the ambient airflow, would allow direct characterization of NPF processes such as the formation and growth rates of newly formed particles. Unfortunately, such Lagrangian observations remain practically unattainable in ambient atmosphere at present. This observational limitation raises a fundamental question: to what extent do the time intervals (the time from when an NPF event is initially observed to when nucleation-mode particles reach the maximum (Zhu et al., 2021)) derived from fixed-site measurements represent the intrinsic evolution of newly formed particles within an air parcel, rather than the effects of spatial inhomogeneity and transport?

Recently, O'Donnell et al. (2025) used 3-D modeling and Lagrangian trajectory analysis to show that Class II events share the same underlying physical mechanisms as classical banana-shaped events, and that their apparent differences mainly arise from spatial inhomogeneity (O'Donnell et al., 2025). Ou et al. (2026) further applied a population balance approach that incorporated transport effects and showed that transport of newly formed particles likely plays an important role in regulating their number concentrations. These recent studies further indicate that the apparent temporal evolution of NPF observed at a fixed site may reflect a combination of in-situ particle formation and growth, spatial heterogeneity, and transport processes. Therefore, before interpreting formation and growth rates from Eulerian observations, it is necessary to distinguish between observed time intervals at a fixed site and the corresponding in-situ time intervals within the moving air parcel. In view of the effects of spatial inhomogeneity and transport on both Class I and Class II events, we first define four technical terms: (1) the time interval over which the net maximum increase in the number concentration of newly formed particles is observed at a fixed site, denoted as $\Delta t_{\text{observe (number)}}$; (2) the in-situ time interval from the onset of NPF to the particle-number peak within the moving air parcel, denoted as $\Delta t_{\text{in-situ (number)}}$; (3) the time interval over which growth of newly formed nucleation-mode particles from the smallest detectable size to a larger size is observed at a fixed site, denoted as $\Delta t_{\text{observe (size)}}$; and (4) the corresponding in-situ growth interval within the moving air parcel over the same size range, denoted as $\Delta t_{\text{in-situ (size)}}$.

Accordingly, (1) $\Delta t_{\text{observe (number)}} = \max(\Delta t_{\text{in-situ (number)}}, \Delta t_{\text{transport-1}})$, where $\Delta t_{\text{transport-1}} = t_2 - t_1$; t_1 is the time when NPF reaches its maximum number concentration in the upwind airflow, and t_2 is the time when that maximum is detected at the fixed site. If $\Delta t_{\text{transport-1}} \leq \Delta t_{\text{in-situ (number)}}$, then $\Delta t_{\text{observe (number)}} = \Delta t_{\text{in-situ (number)}}$. This equality has been implicitly assumed in most previous



65 observational studies of NPF (Kulmala et al., 2004; Chu et al., 2019). However, if $\Delta t_{\text{transport-1}} > \Delta t_{\text{in-situ (number)}}$, then $\Delta t_{\text{observe (number)}}$
 = $\Delta t_{\text{transport-1}}$. In that case, $\Delta t_{\text{observe (number)}}$ is no longer governed by $\Delta t_{\text{in-situ (number)}}$ and therefore cannot be used to calculate the
 true formation rate of newly formed particles.

Similarly, (2) $\Delta t_{\text{observe (size)}} = \max(\Delta t_{\text{in-situ (size)}}, \Delta t_{\text{transport-2}})$, where $\Delta t_{\text{transport-2}}$ is defined analogously to $\Delta t_{\text{transport-1}}$. Again, if
 $\Delta t_{\text{transport-2}} \leq \Delta t_{\text{in-situ (size)}}$, then $\Delta t_{\text{observe (size)}} = \Delta t_{\text{in-situ (size)}}$. This condition has also been widely assumed in the literature (Chu et
 70 al., 2019; Kerminen et al., 2018). However, if $\Delta t_{\text{transport-2}} > \Delta t_{\text{in-situ (size)}}$, then $\Delta t_{\text{observe (size)}} = \Delta t_{\text{transport-2}}$. In that case, $\Delta t_{\text{observe (size)}}$
 cannot be used to calculate the true size-growth rate of newly formed particles. Unfortunately, in previous Eulerian
 observations, no study has been able to determine whether $\Delta t_{\text{observe (number)}}$ corresponds to $\Delta t_{\text{in-situ (number)}}$ or $\Delta t_{\text{transport-1}}$. The same
 applies to whether $\Delta t_{\text{observe (size)}}$ corresponds to $\Delta t_{\text{in-situ (size)}}$ or $\Delta t_{\text{transport-2}}$. From this perspective, the formation and growth rates
 of newly formed particles reported in the literature are all conditional on two assumptions that have rarely been directly
 75 demonstrated.

To address this dilemma, it is useful to reconsider the first principles governing newly formed particles in ambient air.
 Nucleation of the $\text{H}_2\text{SO}_4\text{-H}_2\text{O}$ system in the atmosphere can be hypothesized as a supersaturation-driven phenomenon because
 (1) nucleation often occurs abruptly and decays rapidly, (2) its intrinsic intensity is generally too weak to be directly detected
 in ambient air solely on the basis of observed H_2SO_4 vapor concentrations, and (3) it can be strongly perturbed or enhanced by
 80 NH_3 , amines, highly oxidized organic compounds, cosmic rays, low temperature, turbulence and other factors (Lee et al., 2019;
 Seinfeld and Pandis, 2006; Shen et al., 2026; Tiszenkel et al., 2025; Yin et al., 2021). Such supersaturation is highly unstable
 and may evolve into three broad states. In State 1, supersaturation is disrupted randomly by a short but strong perturbation,
 leading to nucleation within a short period and over a limited spatial scale (Zhu et al., 2017, 2021). In State 2, supersaturation
 and its disruption by a strong perturbation occur over a larger spatial extent, resulting in nucleation that persists for several to
 85 tens of minutes; this type of ambient nucleation broadly corresponds to what is conventionally classified as a Class II NPF
 event (Dal Maso et al., 2005; Lehtipalo et al., 2025). In State 3, supersaturation and its disruption by a strong perturbation
 occur at a regional scale of tens to hundreds of kilometers, leading to nucleation that lasts for hours; this state broadly
 corresponds to what is conventionally classified as a Class I NPF event (Kerminen et al., 2018). In State 1, $\Delta t_{\text{observe (number)}}$ and
 $\Delta t_{\text{observe (size)}}$ should approach the corresponding $\Delta t_{\text{in-situ (number)}}$ and $\Delta t_{\text{in-situ (size)}}$, respectively. In State 3, by contrast, $\Delta t_{\text{observe (number)}}$
 90 and $\Delta t_{\text{observe (size)}}$ are expected to be approximated more closely by $\Delta t_{\text{transport-1}}$ and $\Delta t_{\text{transport-2}}$, respectively, because the
 characteristic spatial and temporal scales are much larger than those in State 1. A similar conceptual framework may also apply
 to State 2, although $\Delta t_{\text{observe (size)}}$ in State 2 is less well constrained.

Guided by this framework, we designed synchronous high-time-resolution measurements to capture short-lived and
 spatially localized NPF processes that are difficult to resolve in conventional Eulerian observations. The indoor observations
 95 were used primarily to examine State 1 and State 2 NPF in semi-enclosed microenvironments, whereas the outdoor
 observations and previously reported ambient Class I events provided references for comparing with State 3 behavior.
 Accordingly, we conducted synchronous high-time-resolution measurements for one month at two separated periods in a



representative indoor environment, together with an additional month of observations between them in ambient air. For the indoor measurements, a condensation particle counter (CPC) with 1 s time resolution and a scanning mobility particle sizer (SMPS) with 3.5 min time resolution were installed on a bench, with their inlets separated by approximately 0.5 m. Such differential responses are not merely instrumental artifacts, but may reflect the rapid transport, diffusion, and spatial heterogeneity of newly formed particle populations within the indoor microenvironment. Particular attention was given to the differential responses of the two instruments when capturing bursts of high-concentration nucleation-mode particles. Based on the observed consistence between instrument responses, we investigated aerosol dynamic characteristics within the indoor microenvironment, with the aim of clarifying the occurrence of State 1 and State 2 NPF in semi-enclosed spaces and the underlying physical mechanisms. Moreover, the small deviations between instruments were used for particle loss correction to obtain more accurate formation rates of newly formed particles. The results were then compared with State 1 and State 2 NPF in the outdoor air and State 3 NPF previously observed in ambient air.

2 Methods

2.1 Sampling site and instruments

Field measurements were conducted in a laboratory located on the third floor of a research facility within a high-tech industrial park in southeastern Hainan Province, China (18.328° N, 109.169° E) during the period from 3 April to 31 May, 2025. During the two-month campaign, laboratory indoor air was measured on 3–12 April and 11–31 May, 2025. The measurements switched to ambient air from 13 April to 10 May. Situated approximately 1.9 km from the South China Sea, the site represents a characteristic land-sea interaction zone. The region is governed by a tropical marine monsoon climate under the influence of the East Asian monsoon system, exhibiting two distinct seasons: a dry season (November–April) dominated by northeasterly continental air masses, and a wet season (May–October) primarily influenced by southeasterly marine air masses.

Indoor observations were performed in a laboratory measuring 9.4 m × 7.5 m × 3.0 m, with a total volume of approximately 211.5 m³. The laboratory was enclosed by concrete walls and large glass curtain walls; the latter were fully covered with blackout roller blinds throughout the experimental period to maintain minimal internal solar irradiance. A dedicated 0.08 m × 0.08 m sampling port was positioned directly above the analytical instruments. This aperture served a dual purpose: it facilitated the introduction of outdoor air into the instruments via conductive tubing and acted as a natural micro-ventilation conduit for air exchange between the indoor and outdoor environments. The laboratory remained in a semi-enclosed state during the study. Environmental conditions were strictly regulated by a central heating, ventilation, and air conditioning (HVAC) system, maintaining the indoor temperature and relative humidity at 23 ± 0.6°C and 66 ± 4%, respectively.

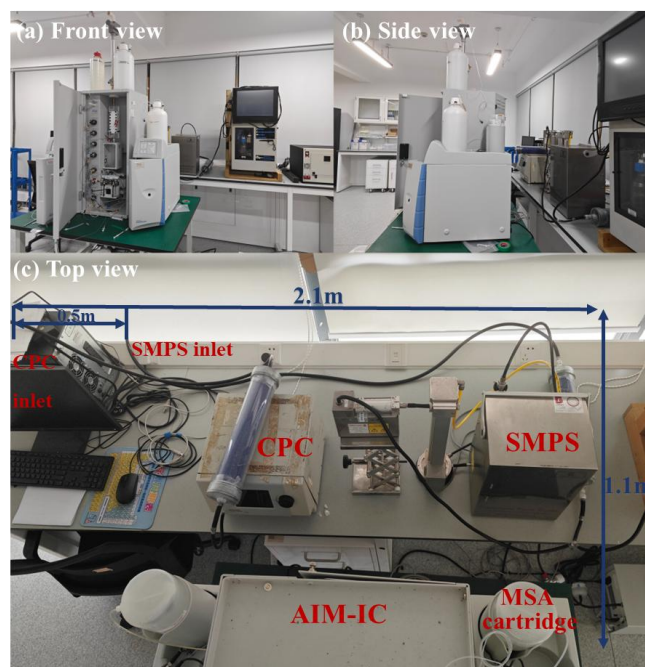


Figure 1: Photographic overview of the experimental setup and instrumentation layout. (a) Front view and (b) side view of the monitoring platform. (c) Top-down view showing the spatial arrangement of the instruments (SMPS, CPC, AIM-IC) and sampling inlets for physical (SMPS and CPC) and chemical measurements using the MSA cartridge. Key dimensions and separation distances are indicated in meters.

In this study, indoor aerosol observations were primarily conducted using a comprehensive suite of instruments, including a SMPS (Grimm, Germany), a CPC (Model 3775, TSI Inc., USA), and a continuous flow cloud condensation nuclei counter (CCNC, DMT Model 100, USA). Simultaneously, an Aerosol Ion Monitor-Ion Chromatography system (AIM-IC; Thermo Fisher, Waltham, MA, USA) equipped with a methanesulfonic acid (MSA) cartridge. The specific spatial configuration of these instruments is illustrated in Fig. 1. Figure 1c provides a detailed plan view of the instrument layout within the laboratory. The sampling inlets of the SMPS and CPC were placed adjacent to each other, with a horizontal spacing of 0.5 m. In contrast, the AIM-IC was positioned away from the wall, with the MSA cartridge at a perpendicular distance of 1.1 m from the blackout roller blind and a horizontal separation of 2.1 m from the CPC inlet.

The SMPS, equipped with a long-DMA, was employed to measure particle size distributions and number concentrations across 129 channels ranging from 10 to 1090 nm, operating with a time resolution of 3.5 min and a flow rate of 0.3 L min⁻¹. The CPC provided real-time measurements of the total number concentration of particles larger than 4 nm at a flow rate of 1.5 L min⁻¹. With a time resolution of 1 s, the CPC operated on a cycle of 55 s of continuous sampling followed by 5 s reserved for data processing and system self-checks every minute. The CCNC was used to measure volume-based cloud condensation nuclei concentrations (N_{CCN}) at a sampling flow rate of 0.45 L min⁻¹ under different supersaturation (SS) conditions. It was calibrated with monodisperse ammonium sulfate particles following the protocol of Rose et al. (2008). Calibration curves relating the temperature gradient in the activation column to the derived supersaturation was established, yielding calibrated



SS levels of 0.21%, 0.33%, 0.54%, 0.70%, and 0.86%. Each SS level was maintained for 5 min, an additional 4 min was allocated to the transition from 0.86% back to 0.21% SS to allow the instrument to re-establish supersaturation equilibrium. To ensure data accuracy, only measurements obtained under stable operating conditions were retained for analysis. Specifically, the final 180 s of each 5 min cycle were used for 0.33%–0.86% SS, and the final 240 s were used for the 0.21% SS level. To minimize particle losses due to electrostatic deposition and to reduce the influence of hygroscopic growth, conductive silicone tubing was used for both the SMPS and CPC sampling lines, and diffusion dryers were installed upstream to maintain the RH of the sample air below 40%. Routine maintenance and calibration procedures were conducted throughout the campaign to ensure measurement accuracy and stability. Further details of the instrumentation and operational procedures can be found in our previous studies (Wang et al., 2019; Zhu et al., 2019).

Simultaneous real-time observations of chemical composition were conducted using the AIM-IC system. For the sampling interface, the system was equipped with a PM_{2.5} cyclone to ensure the precise collection of fine particulate matter at a sampling flow rate of 3 L min⁻¹. The AIM-IC system was equipped with two analytical columns (Ion Pac CS20, 2 × 250 mm for cations; Ion Pac AS 11-HC, 2 × 250 mm for anions) and two guard columns (CG20, 2 × 50 mm for cations; AG 11-HC, 2 × 50 mm for anions). A 5 mmol L⁻¹ methanesulfonic acid solution was used as the eluent, while an H₂O₂ solution served as the absorbent for capturing water-soluble ions. The system provided concentration data for reactive gases and water-soluble ions with an hourly temporal resolution; the detection limit for MSA was 1 × 10⁻⁴ µg m⁻³. More detailed operational information regarding the AIM-IC system is available in our previous studies (Chen et al., 2021; Chen et al., 2022; Huo et al., 2025; Yan et al., 2025). Data points identified as outliers due to instrument malfunction or external contamination events were excluded during quality control to ensure the accuracy and integrity of the dataset.

2.2 NPF relevant parameters

To characterize NPF events, nucleation-mode particles need to be distinguished from pre-existing particles distributed over larger size ranges (Kerminen et al., 2018; Kulmala et al., 2004). Thus, the measured particle number size distributions (PNSDs) were first fitted using a multimodal lognormal distribution function to extract the characteristic parameters for each mode. The fitting equation is expressed as follows:

$$f(D_p, D_{pg,i}, N_i, \sigma_{g,i}) = \sum_{i=1}^n \frac{N_i}{(2\pi)^{\frac{1}{2}} \log(\sigma_{g,i})} \times \exp \left[-\frac{[\log(D_p) - \log(D_{pg,i})]^2}{2 \log^2(\sigma_{g,i})} \right] \quad (1)$$

where D_p denotes the particle diameter and i represents the specific log-normal mode. For each mode i , N_i , $\sigma_{g,i}$, and $D_{pg,i}$ represent the particle number concentration, geometric standard deviation, and geometric mean diameter, respectively. In this study, $D_{pg,1}$ represents the geometric mean diameter of the newly formed particle mode.

Due to the lower detection limit of SMPS at 10 nm, the nucleation mode was frequently only partially captured during NPF events. For the incomplete cases, in which the nucleation-mode maximum occurred at the lower detection limit of the

SMPS (10 nm), $D_{pg,1}$ of 10 nm was assumed. For the remaining incomplete cases, the full nucleation mode size distribution was used for fitting based on symmetry.

For growth and formation rates (GR and FR) of newly formed particles, the calculation methods have been widely documented in the literature (Kerminen et al., 2018; Kulmala et al., 2004).

$$GR = \frac{\Delta D_{pg,1}}{\Delta t} \quad (2)$$

$$J_{10-25} = \frac{\Delta N_{10-25}}{\Delta t_{observe (number)}} + CoagS \times N_{10-25} + \frac{GR}{\Delta D_{p10-25}} \times N_{10-25} \quad (3)$$

where J_{10-25} is the formation rate of particles in the 10–25 nm size range, ΔN_{10-25} (also the NMINP, the net maximum increase in the nucleation-mode particle number concentration) is the net increase of N_{10-25} during $\Delta t_{observe (number)}$, $CoagS$ is the coagulation sink of the preexisting particle population, GR is the growth rate over the 10–25 nm size range and ΔD_p is the diameter interval between 10 and 25 nm. This method, however, can be problematic when the observed number-increase timescale and the observed size-growth timescale do not represent the actual in-situ formation and growth of the same particle population.

The κ was determined using the following equation proposed by Petters and Kreidenweis (2007), as follows:

$$\kappa = \frac{4A^3}{27D_a^3 \ln^2 S_C} \quad (4)$$

$$A = \frac{4\sigma_{s/a} M_w}{RT\rho_w} \quad (5)$$

where D_a represents the minimum dry particle diameter activated at a given supersaturation and is defined as the lower limit of integration when the total integrated particle number concentration, constrained by the maximum particle diameter as the upper limit, equals the N_{CCN} (Cheung et al., 2020; Gao et al., 2020; Hung et al., 2014). S_C is the saturation ratio ($S_C = SS + 1$), M_w is the molecular weight of water, $\sigma_{s/a}$ is the surface tension at the solution-air interface and was assumed to be 0.072 J m^{-2} , ρ_w is the water density, R is the universal gas constant, T is the temperature. The calculated hourly κ values reflected the combined influence of particle size, chemical composition and mixing state, which were referred to as bulk κ values.

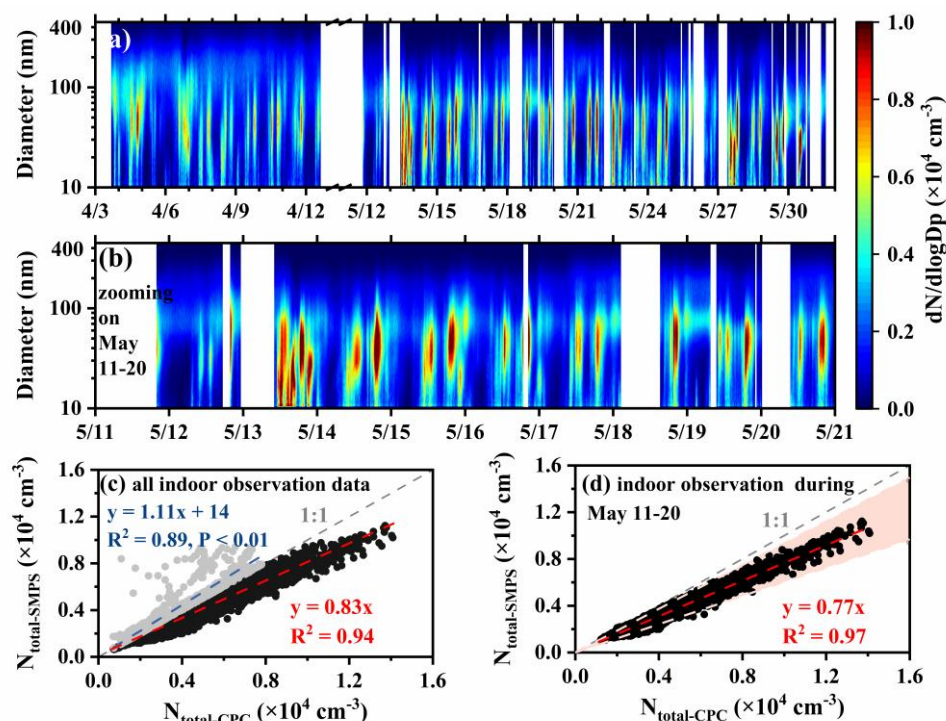
3 Results and discussion

3.1 Overview indoor observations obtained from synchronized SMPS and CPC measurements

Figure 2a-b show contour plots of PNSDs measured by the SMPS and inter-comparisons between the particle number concentration integrated over all SMPS size bins ($N_{total-SMPS}$) during the indoor observation periods of 3–12 April and 11–31 May, 2025. Figure 2c–d present the intercomparison between the particle number concentration integrated over all SMPS size bins ($N_{total-SMPS}$) and the CPC-measured particle number concentration ($N_{total-CPC}$). From 13 April to 10 May, the SMPS, CPC,



205 and other instruments were switched to sample ambient air through the outdoor sampling inlet, and these measurement data are presented in Section 3.3.



210 **Figure 2: Contour plot of PNSDs and intercomparisons between $N_{\text{total-SMPS}}$ and $N_{\text{total-CPC}}$ during indoor observations on 3–12 April and 11–31 May 2025. (a) Contour plot of PNSDs during the entire indoor observations; (b) Same as (a) but zooming on 11–20 May; (c) Intercomparison between $N_{\text{total-SMPS}}$ and $N_{\text{total-CPC}}$ during the entire indoor observations, with gray dots indicate the cases where $N_{\text{total-SMPS}}/N_{\text{total-CPC}} \geq 1$; (d) Same as (c) but only on 11–20 May.**

The comparisons revealed two distinct categories of systematic difference in the SMPS measurement relative to the CPC (Fig. 2c). Category 1, observed on 11–20 May, was characterized by a persistent underestimation of $N_{\text{total-SMPS}}$ compared with $N_{\text{total-CPC}}$ (Fig. 2d). Category 2, which occurred during the remaining indoor observational period, exhibited alternating periods of underestimation and overestimation in different hours of one day (Fig. S1a, b). In Category 2, the underestimation dominated and was comparable in the magnitude to the observed in Category 1, whereas overestimation occurred less frequently, accounting for approximately one quarter of the period in Category 2. Although the $N_{\text{total-SMPS}}$ and $N_{\text{total-CPC}}$ varied substantially during 11 May to 20 May ($(3.6 \pm 1.9) \times 10^3 \text{ cm}^{-3}$ and $(4.6 \pm 2.5) \times 10^3 \text{ cm}^{-3}$, respectively), the ratio of $N_{\text{total-SMPS}}$ to $N_{\text{total-CPC}}$ remained consistently below unity (Fig. 2d). Linear regression analysis with the intercept constrained to zero yielded a slope of 0.77 ($R^2 = 0.97$), indicating an apparent systematic underestimation by 23% in the SMPS measurements relative to the CPC. This discrepancy likely represents the upper limit of systematic difference due to a combination of the SMPS' low transmission efficiency for particles smaller than 10 nm (Hermann et al., 2007; Kangasluoma et al., 2015; Kangasluoma et al., 2020; Li et al., 2024; Wiedensohler et al., 2012), diffusion losses inherent to the SMPS, and possible differences in instrument response



in the indoor observation environment. Nevertheless, the high R^2 value demonstrates that the SMPS faithfully captured the
 225 temporal variability of particle number concentrations. Therefore, the complementary use of CPC and SMPS provides a
 reliable basis for estimating FR and GR during States 1 and 2. Note that the systematic underestimation by 23% in the SMPS
 measurements relative to the CPC was derived primarily from the loss of nucleation mode particles on the basis of source
 apportionment analysis, as presented in Text S1 and Fig. S2 and S3.

Building on the approximately 23% systematic difference of $N_{\text{total-SMPS}}$ relative to $N_{\text{total-CPC}}$ identified for Category 1,
 230 Category 2 was further examined to assess the consistency between the two instruments and to evaluate the occurrence
 frequency of cases in which $N_{\text{total-SMPS}}$ exceeded $N_{\text{total-CPC}}$. Category 2 was first divided into two subsets: Category 2a with $N_{\text{total-SMPS}}/N_{\text{total-CPC}} < 1$, and Category 2b with $N_{\text{total-SMPS}}/N_{\text{total-CPC}} \geq 1$. Because the latter ratio is opposite to the systematic difference
 observed in Category 1, these cases were analyzed separately. Regression analysis of the combined Category 1 and Category
 2a data, with the intercept constrained to zero, yielded a slope of 0.83 ($R^2 = 0.94$). The high R^2 value again indicates the strong
 235 temporal consistency between the two instruments. Compared with the slope of 0.77 obtained for Category 1 alone, the slightly
 higher slope suggests that additional factors partially offset the systematic difference observed in Category 1. The Category
 2b subset ($N_{\text{total-SMPS}}/N_{\text{total-CPC}} \geq 1$) was then analyzed independently. The subset accounted for 17% of the entire indoor data.
 Again, regression analysis of this subset yielded $N_{\text{total-SMPS}} = 1.1 \times N_{\text{total-CPC}} + 14$, $R^2 = 0.89$, $P < 0.01$. Consistent with this
 slope of 1.1, frequency analysis further showed that cases with $N_{\text{total-SMPS}}/N_{\text{total-CPC}} \geq 1.1$ and ≥ 1.2 accounted for 6% and 2%
 240 of the total dataset, respectively. Although the slightly lower R^2 indicates greater variability than that of the bulk dataset, the
 appreciable occurrence probability of these events suggests that they should be regarded as genuine probabilistic events, i.e.,
 State 1 events occurred in substantially small spatial and temporal scales, rather than random noise.

3.2 Case analysis of $\Delta t_{\text{observe}}$, FR and GR of newly formed particles in indoor air

In this section and section 3.3, a case-by-case analysis was conducted to examine the calculation of $\Delta t_{\text{observe}}$, FR, and GR
 245 of newly formed particles under State 1 and State 2 conditions driven by different condensing vapors. Cases 1–4 were observed
 in indoor air and presented in this section. Cases 1 and 2 occurred on 13–14 May and were likely driven by organic vapors
 introduced through ventilation from outdoor air, on the basis of the estimated κ values during the period (Fig. 3). During the
 two cases, the N_{total} measured by the SMPS and CPC were highly correlated and exhibited a nearly constant bias (Fig. 3b, h).
 These two cases therefore used as reference cases for comparison with the others. Cases 3 and 4 were observed during nighttime
 250 and daytime, respectively, on 24 May (Fig. S4), and were most likely associated with the indoor release of MSA vapor from
 the MSA cartridge installed in the AIM-IC system (identical unexpectedly high MSA concentrations $\geq 0.1 \mu\text{g m}^{-3}$ were detected
 both at the gas and particle phases, which were not shown here). Section 3.3 presents Cases 5–9, during which both instruments
 sampled outdoor air (Fig. 4 and Fig. S5). For example, Case 5 corresponded to a typical Class II event driven by mixed H_2SO_4 -
 organic vapors observed on 11 May (Fig. S5). Such highly localized NPF events provided cases in which $\Delta t_{\text{observe}}$ may be more



likely to approach $\Delta t_{in-situ}$. Overall, Cases 1-9 represent approximately 90% of the short-term daytime and nighttime NPF event types observed during the study period.

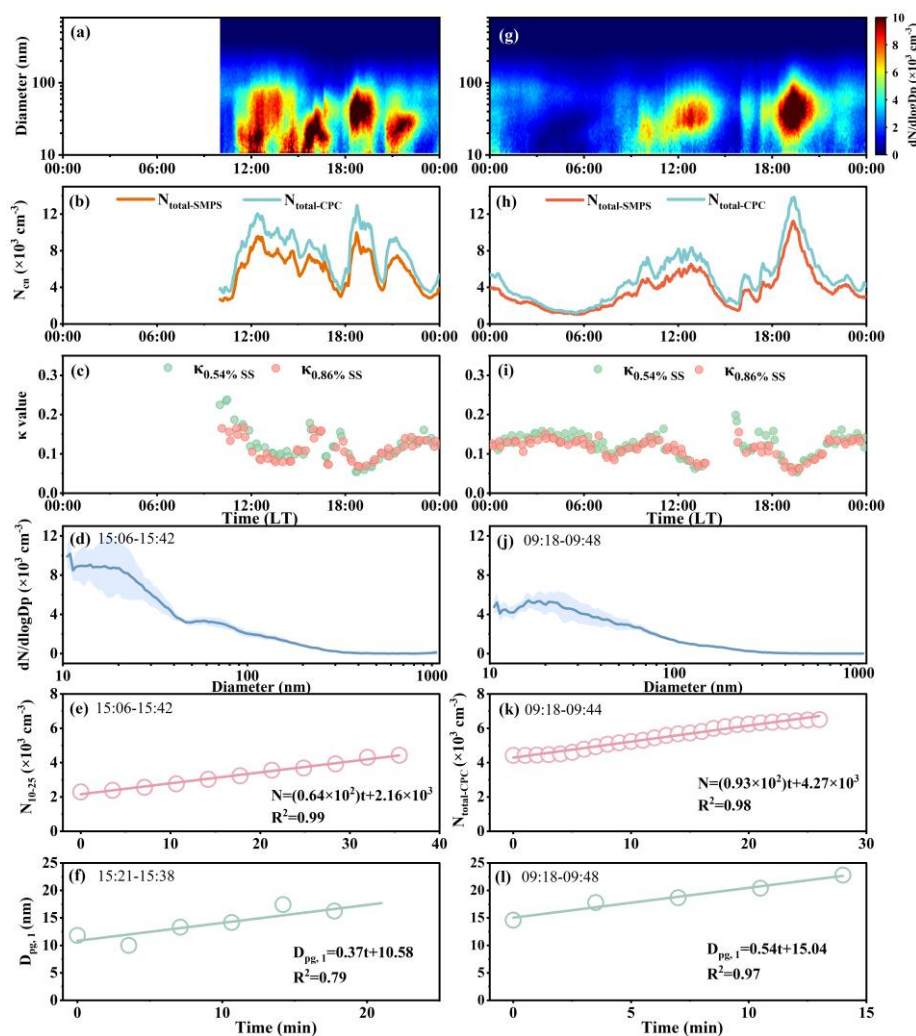


Figure 3: Comparison of two indoor NPF events observed on 13 May 2025 (Case 1, a–f) and 14 May 2025 (Case 2, g–l). (a, g) temporal evolution of PNSDs; (b, h) total particle number concentrations measured by SMPS and CPC ($N_{total-SMPS}$ and $N_{total-CPC}$); (c, i) κ values retrieved at different SS; (d, j) mean PNSDs with standard deviations; (e, k) temporal evolution and linear regression of newly formed particle number concentration; (f, l) temporal evolution and linear regression of the $D_{pg,1}$.

Figure 3 showed two short-term NPF events to be observed on 13 May and one on 14 May. Strong cooking emissions caused pronounced spikes in N_{total} during 12:00–13:00 (lunch time) and 18:00–20:00 (dinner time), with similar PNSDs characteristics. On 13 May, one NPF event began before lunch and subsequently overlapped with cooking emissions. Two additional NPF events were detected immediately after lunch and dinner, respectively, and both were evidently influenced by



residual particles in the ventilation system. The event occurred between 15:06 and 15:42 experienced the least interference from cooking emissions and was therefore selected to characterize $\Delta t_{\text{observe}}$, FR, and GR of newly formed particles (Case 1). During this 36 min event, N_{10-25} measured by the SMPS nearly doubled, increasing from 2.3×10^3 to $4.4 \times 10^3 \text{ cm}^{-3}$. Meanwhile, N_{total} measured by the SMPS and the CPC were highly correlated with R^2 of 0.98. When the regression intercept was constrained to zero, the relationship was $N_{\text{total-SMPS}} = 0.78 \times N_{\text{total-CPC}}$, $R^2 = 0.99$. Using $\Delta t_{\text{observe (number)}} = 36 \text{ min}$, the corresponding particle loss corrected FR was estimated to be $3.5 \text{ cm}^{-3} \text{ s}^{-1}$. In contrast, $\Delta t_{\text{observe (size)}}$ cannot be assumed to equal 36 min because the modal diameter evolution was not continuous throughout the event. Specifically, the estimated $D_{\text{pg},1}$ narrowly varied from $<10 \text{ nm}$ to 11.9 nm during 15:06–15:24, whereas it stabilized between 16.2 nm and 17.4 nm during 15:34–15:42. Therefore, the 17 min period from 15:21 to 15:38 was used as $\Delta t_{\text{observe (size)}}$, yielding a corresponding GR of 22 nm h^{-1} .

This interpretation is further supported by particle number conservation. Nucleation-mode particles with an initial modal diameter below 10 nm and a concentration of $2.3 \times 10^3 \text{ cm}^{-3}$ could not have simply grown to a modal diameter of 16.9 nm while their concentration simultaneously doubled to $4.4 \times 10^3 \text{ cm}^{-3}$. Condensational growth alone does not increase total particle number concentration, whereas coagulation and other growth-related processes would be expected to reduce it. It is therefore reasonable to infer that at least $2.1 \times 10^3 \text{ cm}^{-3}$ additional particles entered the detectable size range during this period, representing newly formed particles that subsequently grew to larger sizes. Assuming that particle formation started at $\sim 2 \text{ nm}$ and required 36 min to reach the observed modal diameter of 16.9 nm , the corresponding GR would be approximately 25 nm h^{-1} , which agrees well with the value (22 nm h^{-1}) derived from the observed size evolution. This agreement supports the validity of the proposed method for estimating GR.

On 14 May, Case 2 NPF event was first detected at 09:19 and reached its maximum at 09:44. Accordingly, $\Delta t_{\text{observe (number)}}$ was 25 min, corresponding to a particle-loss-corrected FR of $2.7 \text{ cm}^{-3} \text{ s}^{-1}$. In contrast, the $D_{\text{pg},1}$ remained nearly constant at $14.3\text{--}15.1 \text{ nm}$ between 09:19 and 09:34 before increasing continuously to 22.8 nm at 09:48. Consequently, $\Delta t_{\text{observe (size)}}$ was determined to be 14 min, yielding a GR of 33 nm h^{-1} , which is reasonably consistent with the estimate obtained for the 13 May event.

Figure S4 showed that multiple short-term NPF events were detected before sunrise (06:10 LT) on May 24. The strongest event occurring between 02:38 and 02:48 (Case 3) was selected for detailed analysis. During the 10 min event, N_{10-25} increased from $0.61 \times 10^3 \text{ cm}^{-3}$ to $1.7 \times 10^3 \text{ cm}^{-3}$, while the $N_{\text{total-CPC}}$ increased by $2.5 \times 10^3 \text{ cm}^{-3}$. The corresponding particle-loss-corrected FR was estimated to be $7.5 \text{ cm}^{-3} \text{ s}^{-1}$. Because the $D_{\text{pg},1}$ remained $\leq 10 \text{ nm}$ throughout the event, GR could not be determined. After 09:00 LT, a series of additional short-term NPF events were observed until 11:30. These events were likely superimposed on a regional NPF event and were therefore influenced by spatial inhomogeneity. The strongest event occurred between 09:11 and 09:33 (Case 4). During the 22 min period, the NMIMP derived from N_{10-25} was $1.5 \times 10^3 \text{ cm}^{-3}$ and exhibited a strong linear relationship with $N_{\text{total-CPC}}$ ($R^2 = 0.98$). The corresponding NMIMP derived from $N_{\text{total-CPC}}$ was $3.4 \times 10^3 \text{ cm}^{-3}$, yielding a particle-



loss-corrected FR of $2.7 \text{ cm}^{-3} \text{ s}^{-1}$. The $D_{pg,1}$ fluctuated from $\leq 10 \text{ nm}$ to 12 nm during the event. Assuming that the particle
 300 formation started at $\sim 2 \text{ nm}$ the particles required 22 minutes to reach 12 nm , corresponding to a GR of 27 nm h^{-1} .

3.3 Case analysis of $\Delta t_{\text{observe}}$, FR and GR of newly formed particles in outdoor air

On 11 May, strong NPF events were observed around noon and during the afternoon (Fig. S5 a-f). Based on the estimated κ values, these events were most likely driven by the combined condensation of H_2SO_4 and organic vapors under enhanced daytime photochemical conditions. One of the strongest events occurred between 14:34 and 14:41 (Case 5). During the 7 min
 305 period, $N_{\text{total-CPC}}$ increased from 1.1×10^4 to $1.5 \times 10^4 \text{ cm}^{-3}$, with an NMIMP of $4.3 \times 10^3 \text{ cm}^{-3}$. The correlation between $N_{\text{total-SMPS}}$ and $N_{\text{total-CPC}}$ was relatively high at 14:00-15:00, with an R^2 value of 0.99. Using $\Delta t_{\text{observe (number)}} = 7 \text{ min}$, the corresponding particle-loss-corrected FR was estimated to be $18 \text{ cm}^{-3} \text{ s}^{-1}$. Meanwhile, the fitted geometric mean diameter of the nucleation mode increased from 22.8 to 28.9 nm during the event. Therefore, $\Delta t_{\text{observe (size)}}$ was taken as 7 min, yielding a corresponding GR of 52 nm h^{-1} .

Figure 4 shows that a strong NPF event occurred between 10:15 and 11:05 on 13 April immediately after a rain shower (Case 6). During the initial stage of the event (10:15–10:33), the N_{10-25} exhibited substantial fluctuations. The FR was calculated as $3.4 \text{ cm}^{-3} \text{ s}^{-1}$ from 10:37 to 10:58, when N_{10-25} doubled and the NMIMP was $3.7 \times 10^3 \text{ cm}^{-3}$. Because the CPC did not operate properly during this period, the particle-loss-corrected FR was estimated from the statistical bias of the SMPS, yielding a value of $4.4 (3.4/0.78) \text{ cm}^{-3} \text{ s}^{-1}$. This correction should be interpreted cautiously because the CPC and SMPS have
 315 different lower detection limits and their concentration ratio may vary with the PNSDs. The $D_{pg,1}$ also exhibited considerable variability, reaching a maximum of 13.4 nm . Following the same approach described above, the corresponding GR was estimated to be 33 nm h^{-1} . A second short term NPF event was observed between 06:19–06:29 on 14 April (Case 7), superimposed on a regional NPF event. The regional NPF likely initiated during the nighttime and was influenced by spatial inhomogeneity. Unlike the previous cases, the short-term NPF event was characterized by a relatively large $D_{pg,1}$ of 33 nm .
 320 Consequently, the N_{10-25} was used to estimate FR based on an NMIMP of $7.5 \times 10^3 \text{ cm}^{-3}$ over 10 min, yielding a particle-loss-corrected FR of $4.5 \text{ cm}^{-3} \text{ s}^{-1}$. Assuming that the newly formed particles grew from $\sim 2 \text{ nm}$ to 33 nm in the 10 minutes, the corresponding GR was estimated to be 186 nm h^{-1} .

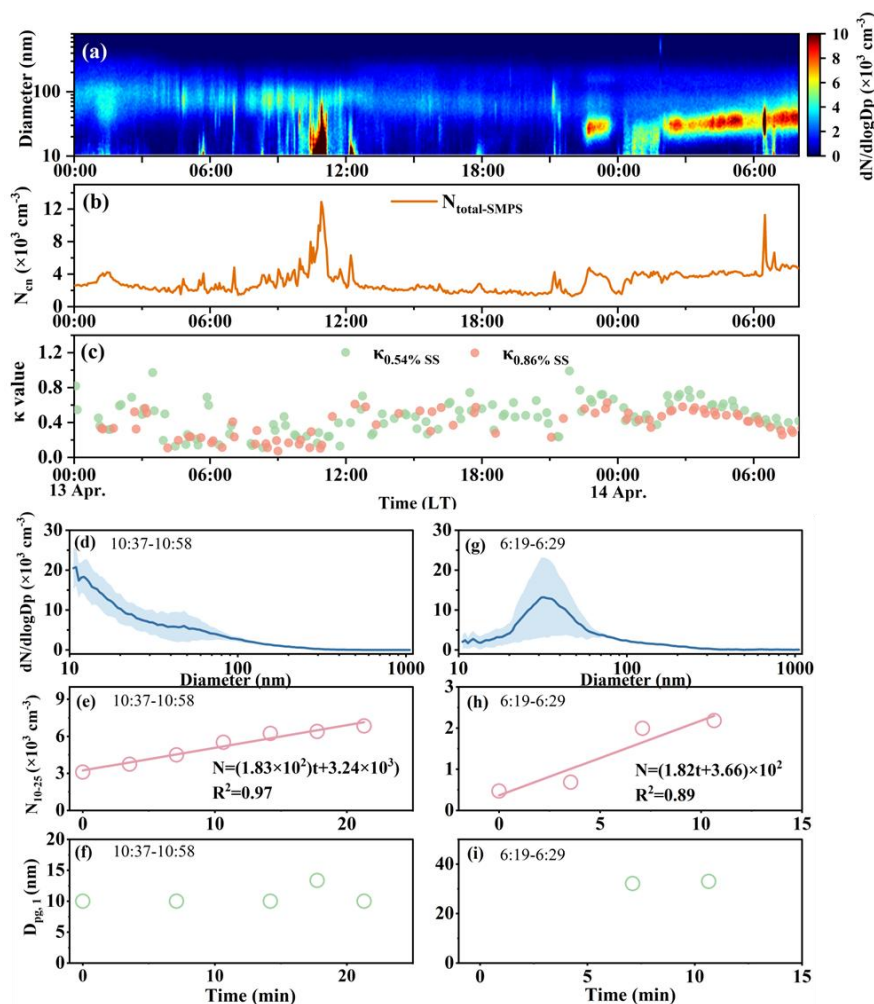


Figure 4: Comparison of two outdoor NPF events observed on 13 April 2025 (Case 6) and 14 April 2025 (Case 7). (a–c) Overview of the observations during 13–14 April; (a) temporal evolution of PNSDs; (b) total particle number concentrations measured by SMPS; (c) κ values retrieved at different SS; (d, g) mean PNSDs with standard deviations; (e, h) temporal evolution and linear regression of newly formed particle number concentration; (f, i) temporal evolution of the $D_{pg,1}$.

Case 8 occurred during 01:22–01:33 on 20 April (Fig. S5). During this 11 min period, $N_{\text{total-CPC}}$ increased more substantially from 6.6×10^3 to $1.0 \times 10^4 \text{ cm}^{-3}$, corresponding to a minimum background-level newly formed particle number concentration. During the hour of this event, $N_{\text{total-SMPS}}$ and $N_{\text{total-CPC}}$ were highly correlated, with an R^2 value of 0.95. Using $\Delta t_{\text{observe (number)}} = 11 \text{ min}$, the corresponding particle-loss-corrected FR was estimated to be $12 \text{ cm}^{-3} \text{ s}^{-1}$. The $D_{pg,1}$ changed from 15.3 to 15.8 nm during the event. The corresponding κ values suggested that this event was likely driven mainly by H_2SO_4 -related vapors, with a possible minor contribution from organic vapors. Assuming that the newly formed particles grew from $\sim 2 \text{ nm}$ to 15.8 nm within the 11 min period, the GR equals 75 nm h^{-1} .

Case 9 was observed from 23:02 to 23:09 on 20 April (Fig. S5). During this period, $N_{\text{total-CPC}}$ increased from 1.2×10^4 to

$2.0 \times 10^4 \text{ cm}^{-3}$, with an NMINP of $7.7 \times 10^3 \text{ cm}^{-3}$. The corresponding N_{10-25} increased from 6.2×10^3 to $8.4 \times 10^3 \text{ cm}^{-3}$. During the hour of this event, $N_{\text{total-SMPS}}$ and $N_{\text{total-CPC}}$ were highly correlated, with an R^2 value of 0.96. Using $\Delta t_{\text{observe (number)}} = 7 \text{ min}$, the corresponding particle-loss-corrected FR was estimated to be $21 \text{ cm}^{-3} \text{ s}^{-1}$. The fitted geometric mean diameter of the nucleation mode reached 18.5 nm by the end of the event. Therefore, $\Delta t_{\text{observe (size)}}$ was taken as 7 min, yielding a corresponding GR of 34 nm h^{-1} . This nighttime event was more likely associated with the intrusion of organic-rich plumes, which provided condensable organic vapors for rapid particle formation and early growth under weak photochemical conditions, on the basis of the estimated κ values.

3.4 Comparison of short-term FR and GR of newly formed particles with those in Class I events

The relationships between GR and D_{pgmax} (the maximum geometric mean diameter of newly formed particles) and between FR and NMINP for Cases 1–9 in this study are compared with previously reported 160 regional NPF events in Fig. 5. The nine cases (yellow open circles) exhibit markedly different characteristics from the historical observations (solid symbols). The distinct distributions indicated that the derived FR and GR are highly sensitive to the observational time and spatial scale used in their calculation. The exceptionally high FR and GR observed for Cases 1–9 suggest that newly formed particles may grow from initial clusters or extremely small particles to the nucleation mode, and even to the Aitken mode size range, over a time scale much shorter than the $\Delta t_{\text{observe (size)}}$ commonly inferred from conventional Eulerian observations. This suggests that the continuous size growth observed during classical banana-shaped NPF events at a fixed site does not necessarily represent the true in-situ growth of the same particle population within the same air parcel.

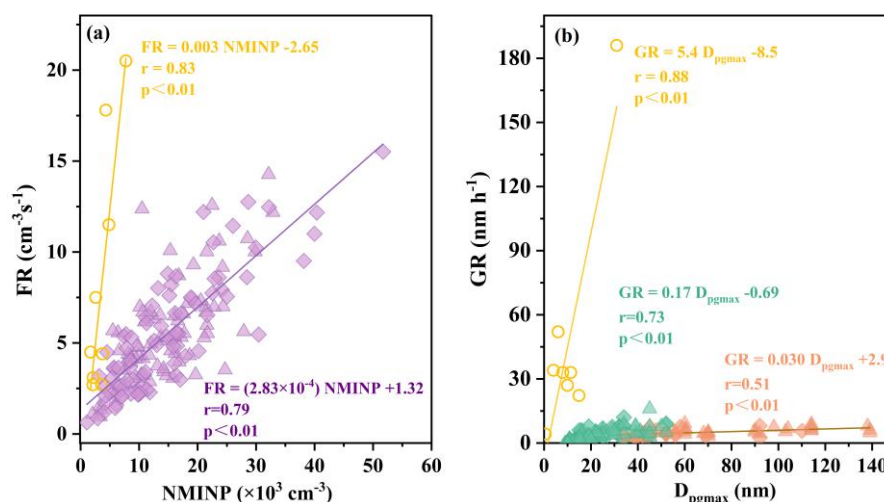


Figure 5: Comparison of the (a) FR–NMINP and (b) GR– D_{pgmax} relationships between the NPF events observed in this study and previously reported events. Solid lines represent linear regression results, with the corresponding regression equations, Pearson correlation coefficients, and significance levels shown in each panel. Open yellow circles denote the new data from this study (Cases 1–9), whereas solid symbols represent historical observations adapted from *Zhu et al. (2021)*. Triangles and hexagons indicate NPF events observed at the Qingdao site during 2010–2012 and 2016–2018,



360 **respectively. In panel (b), green and orange symbols denote one-stage-growth and multi-stage-growth NPF events, respectively.**

Traditional regional NPF events often persist for several hours or longer, during which D_{pgmax} can reach several tens to more than one hundred nanometers. However, because the corresponding $\Delta t_{observe (size)}$ is generally long, the calculated GR values are mostly below 20 nm h^{-1} . In contrast, the Cases 1–9 data demonstrate that substantial particle growth can occur over
 365 a much shorter time interval, resulting in considerably higher apparent growth rates even when the particles remain within the nucleation mode size range. Thus, the relatively low GR derived from conventional Eulerian observations may primarily represent an apparent average changing rate of modal diameter evolution at a fixed observation site, rather than the intrinsic growth rate of newly formed particles within an air parcel. If $\Delta t_{observe (size)}$ includes the effects of transport, spatial inhomogeneity, or the sequential passage of different particle populations across the sampling site, the calculated GR may be substantially
 370 lower than the actual in-air-mass growth rate. The underestimate might further mislead the analysis on particle growth mechanisms such as drivers, pathways, etc. Note that the FR and GR values of regional NPF events reported in the literature, e.g., reviewed by Kulmala et al., 2004 and Chu et al., 2019, mostly suffered from the challenge same as analyzed in Case 1, i.e., nucleation-mode particles with an initial modal diameter below 10 nm could not have simply grown to a modal diameter > 10 nm while their concentration simultaneously doubled.

375 The individual cases further illustrate the short time scales associated with particle growth. In Cases 1 and 2, although the increase in particle number concentration lasted for several tens of minutes, the $\Delta t_{observe (size)}$ used to characterize particle growth was much shorter than the entire event duration. In Cases 7–9, newly formed particles reached sizes of several tens of nanometers within approximately 7–11 min. These results indicate that the growth of newly formed particles from their initial small sizes to the nucleation mode or larger size ranges resolvable by the SMPS does not necessarily require the several-hour
 380 time scale typically inferred from regional NPF events. It should be emphasized that the $\Delta t_{observe (size)}$ used in this study is still constrained by the SMPS scanning cycle, the lower detection limit of particle size, and the event-identification approach. Therefore, it more likely represents an upper limit of the true $\Delta t_{in-situ (size)}$, rather than an exact value.

Similarly, for FR, the basic term dN/dt directly depends on the selected $\Delta t_{observe (number)}$. The final FR further includes corrections for coagulation loss and particle growth out of the considered size range. Therefore, when $\Delta t_{observe (number)}$ does not
 385 represent the true $\Delta t_{in-situ (number)}$, the derived FR should also be interpreted as an apparent formation rate based on the observational time scale, rather than an intrinsic rate of new particle formation.

Overall, the results highlight an important limitation in the interpretation of FR and GR derived from fixed-site Eulerian observations. Both parameters implicitly rely on the assumption that the temporal evolution of particle number concentration and particle size observed at a fixed site reflects the formation and growth of the same newly formed particle population within
 390 a relatively homogeneous air parcel. When this assumption is not satisfied, FR and GR may represent apparent rates of particle evolution at the observation site rather than intrinsic in-air-mass formation and growth rates. This distinction is particularly important when comparing NPF events occurring over substantially different temporal and spatial scales. FR and NMNP



provide complementary measures of NPF intensity, whereas GR and D_{pgmax} characterize particle growth. NMINP represents the maximum net increase in newly formed particle number and therefore more directly reflects the particle production magnitude of an event. D_{pgmax} represents the maximum size attained by the newly formed particle population and provides information on its potential to evolve toward CCN-relevant sizes. In contrast, FR and GR describe the rates at which particle number and size change and are therefore inherently more sensitive to the choice and representativeness of $\Delta t_{observe}$. Accordingly, FR and GR should be interpreted together with NMINP and D_{pgmax} and in the context of the temporal and spatial scales over which they are derived.

400 4 Conclusion and Implication

This study highlights the importance of observational timescales in interpreting FR and GR derived from fixed-site measurements. When the observed temporal evolution does not represent the formation and growth of the same newly formed particle population within a relatively homogeneous air parcel, the derived rates may reflect apparent particle evolution at the observation site rather than intrinsic in-air-mass processes.

405 The nine short-term NPF cases examined in this study demonstrate that substantial particle-number increases and growth to tens of nanometers can occur within several to tens of minutes. The analyses further show that particle-number increase and particle-size evolution may occur over different observational timescales within the same NPF event, highlighting the importance of assessing whether the selected $\Delta t_{observe}$ adequately represents the corresponding formation or growth process. For several short-lived events, the resulting apparent FR and GR were considerably higher than values commonly reported for long-lasting regional NPF events. These differences illustrate the strong sensitivity of rate-based metrics to the temporal and spatial scales over which they are derived, although fixed-site observations alone cannot determine the magnitude or direction of their deviation from the corresponding intrinsic in-air-mass rates.

415 NMINP and D_{pgmax} provide important complementary information on the magnitude of newly formed particle production and the extent of particle growth, respectively, while being less directly dependent on the selected observational time interval than FR and GR. Accordingly, FR and GR should be interpreted together with these event-scale metrics and, more importantly, in the context of the choice and representativeness of $\Delta t_{observe}$. Overall, this study strongly suggested that all FR and GR previously reported in the literature should be re-examined by constraining the relationship between Eulerian observational timescales and intrinsic particle formation and growth processes. However, their NMINP and D_{pgmax} should still be valid for comparing NPF intensity and growth extent globally.

420 Data availability

The data are available upon request via the following link: <https://data.mendeley.com/preview/k2b5sn4m3t?a=4761e3b3-9b25-45a9-be47-51a27fd85226>.



Author contributions

425 ZK contributed to the investigation, data curation, formal analysis, and writing of the original draft. QF and LS contributed to the investigation, data curation, and writing – review and editing. YG and HG contributed to the writing –review and editing. YZ contributed to the conceptualization, formal analysis, validation, resources, and writing – review and editing. XY contributed to the conceptualization, methodology, supervision, and writing – review and editing. All authors reviewed and approved the final manuscript.

Competing interests

430 The authors declare that they have no conflict of interest.

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