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Quiet New Particle Formation is a significant aerosol source in the Amazon boundary layer

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Abstract. Aerosol particles formed by new particle formation (NPF) are essential for cloud condensation nuclei and can strongly influence cloud properties and climate. However, the mechanisms behind NPF in the Amazon boundary layer have remained elusive. Classical "banana" NPF events, common in other continental regions, are rarely observed in the Amazon, while most detected sub-50 nm particles have been linked to precipitation- and downdraft-related episodes, often called Amazonian banana events. Here, we analyse a decade of particle number size distributions (10–420 nm) from the Amazon Tall Tower Observatory (ATTO) during the wet season and demonstrate the presence of a distinct phenomenon called Quiet NPF. This process represents a subtle but persistent background particle formation, occurring on days without clear banana-type growth signatures. Using a statistical approach, we show that Quiet NPF links freshly formed 10 nm particles to growth into the Aitken mode. This mechanism is characterized by a growth rate of 2.3 ± 0.1 nm h^{-1}, about half that of Amazonian banana events, but occurs much more frequently. Quiet NPF accounts for ~45% of 10–25 nm particle production during the wet season, revealing an overlooked but important source of nanoparticles that contributes to sustaining Amazonian aerosol populations.

1 Introduction

New Particle Formation (NPF) contributes to atmospheric aerosols globally, influencing cloud condensation nuclei (CCN) and the climate (Spracklen et al., 2008; Gordon et al., 2017). Typically identified by a distinct "banana" shape in particle number size distribution (PNSD) plots, classical NPF events involve the nucleation of particles at ~1–3 nm and subsequent growth (Dal Maso et al., 2005; Kulmala et al., 2013; Dada et al., 2018). Recent studies revealed continuous but subtle aerosol formation, termed "Quiet NPF," occurring on days classified as non-event days due to the absence of clear nucleation

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and growth signatures (Kulmala et al., 2022a, 2024). Thus, focusing only on NPF events biases studies toward intense cases. This quiet mechanism can substantially contribute to particle numbers annually, particularly where classical NPF events are infrequent (Kulmala et al., 2022a).

In Amazonia's wet season, aerosol composition is characterized by a prevalence of biogenic secondary organic aerosols (SOA) resulting from volatile organic compound (VOC) oxidation (Pöschl et al., 2010; Artaxo et al., 2013, 2022; Chen et al., 2015), though occasional intrusions of long-range transported African aerosols occur (Valiati et al., 2025). However, classical NPF events, as observed in boreal or mid-latitude regions, are notably absent in the Amazon boundary layer (BL). Instead, observational studies in the boundary layer typically find only sparse regional NPF events, with most sub-50 nm particles linked to convective downdrafts that transport particles from aloft (Rizzo et al., 2018; Machado et al., 2021; Franco et al., 2022, 2024). New particle formation at low heights has therefore been primarily attributed to vertical transport from upper-tropospheric nucleation (Martin et al., 2010; Andreae et al., 2018; Zhao et al., 2022, 2024). Flight field observations, chamber studies, and box models have indicated that, in the Amazonian upper troposphere, isoprene oxidation generates highly oxygenated molecules (HOMs) — specifically extremely-low-volatility and ultra-low-volatility organic compounds (ELVOCs and ULVOCs) — driving substantial NPF (Curtius et al., 2024; Shen et al., 2024; Bardakov et al., 2024).

Nevertheless, uncertainty persists regarding boundary-layer aerosol formation. Recent studies highlight potential local and regional nucleation processes close to the canopy, driven by rainfall events and challenging existing assumptions (Machado et al., 2024). Numerical simulations also indicate that the vertical transport of newly nucleated ultrafine particles from the upper troposphere to the boundary layer is inefficient on time scales of a few days (Wang et al., 2023). Crucially, the chemical mechanisms controlling these local processes remain poorly characterized, with ongoing debates surrounding the roles of isoprene, monoterpenes, and sesquiterpenes (Heinritzi et al., 2020; Dada et al., 2023).

In this study, we analyzed a decade-long (2014-2023) record of aerosol size distributions from the Amazon Tall Tower Observatory (ATTO) during its wet season (January – May), when the atmosphere best reflects natural background conditions. Using a novel statistical approach (Kulmala et al., 2022a), we demonstrate the presence and significance of Quiet NPF in the Amazon boundary layer, characterising its unique formation and growth dynamics and quantifying its contribution to sub-50 nm aerosol populations.

2 The Characteristics and Relevance of Quiet NPF in the Amazon

2.1 Identification of Quiet NPF through Diurnal Dynamics of Particle Size Distributions

This study identifies and characterizes Quiet NPF during non-event days within the Central Amazon boundary layer during its wet season. Quiet NPF differs from both classical NPF events—high formation rate episodes rarely observed in the Amazon—and from the more frequent "Amazonian bananas" (i.e., rainfall/downdraft-related events, with lower particle concentrations and higher initial diameters). Both classical events and Amazonian bananas exhibit clear, banana-shaped features in PNSDs. In contrast, Quiet NPF is a subtle and persistent process that lacks such distinct signatures. By examining

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median diurnal cycles from extensive datasets, we reduce noise and ambient inhomogeneities effects, revealing the typical behaviour and daily growth dynamics of Quiet NPF in this environment.

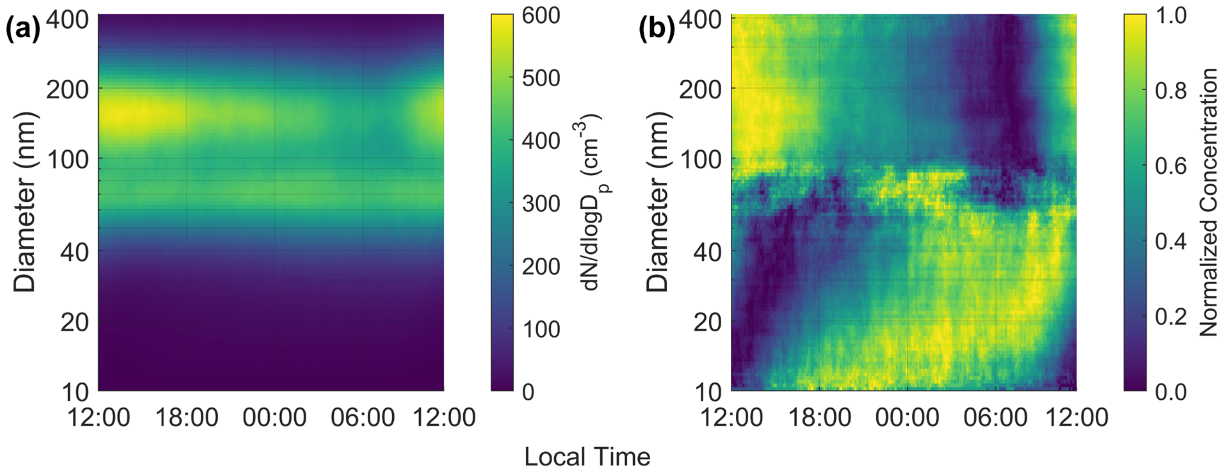

Figure 1. Median diurnal cycle of the (a) absolute and (b) normalized particle number size distribution during non-event days at the Amazon Tall Tower Observatory (ATTO) from 2014 to 2023 during the wet season. Panel (a) does not show visible particle growth, emphasising the subtle nature of Quiet NPF. Panel (b) enhances the visibility of particle growth by normalizing concentrations in each diameter bin, clearly illustrating slow, sequential particle growth from around 10 nm to Aitken-mode size, characteristic of Quiet NPF.

Figure 1 illustrates the median diurnal cycle of the (a) absolute and (b) normalized PNSD observed during non-event days at ATTO. The absolute PNSD (**Fig. 1a**) primarily shows the dynamics of accumulation and Aitken mode particles, which are influenced by boundary layer processes such as nocturnal deposition and daytime turbulent mixing. Notably, this panel does not reveal clear particle growth, showing the subtlety of Quiet NPF, which is obscured by the dominance of larger particle modes.

In contrast, the normalized PNSD shown in **Fig. 1b** presents daily maxima and minima for each diameter bin, scaled independently from 0 to 1. Larger particles (diameter > 100 nm) exhibit relatively homogeneous diurnal behaviour, reflecting their common response to variations in boundary layer height. Smaller particles (diameter < 50 nm) demonstrate significant size-dependent dynamics, with ~10 nm peaks at 18:00 followed by progressively larger peaks, culminating at ~60 nm by noon the next day.

A similar pattern was also observed in an independent analysis of the PNSD during the wet seasons of 2008–2014 at the nearby ZF2 site in the Central Amazon. Despite the coarser resolution, they reveal an identical nocturnal growth pattern with sub-50 nm particle concentrations peaking at night (**Fig. S1**). This consistency across sites in the Amazon underscores the regional significance of Quiet NPF, a process characterized by subtle growth signatures that become apparent only through detailed statistical normalization.

Meteorological analyses further elucidate Quiet NPF. Non-event days show predominantly positive median diurnal $\Delta\theta_e$ (**Fig. S2**), indicating a minimal influence from convective downdrafts. This supports a primarily boundary-layer-driven process for

Quiet NPF, independent of upper tropospheric transport. In contrast, event days display the lowest negative $\Delta\theta_e$ values during the morning, coinciding with the highest precipitation frequency and aligning with known associations between Amazonian-banana events, precipitation, and convective downdrafts (Franco et al., 2022; Machado et al., 2024).

Interestingly, Aitken-mode particles within the 60–85 nm size range exhibit a distinct peak around midnight, unlike most other particle size ranges. This is potentially associated with nocturnal emissions of primary biogenic particles in the Aitken size range, as previously documented (Pöhlker et al., 2012; Rizzo et al., 2018; Glicker et al., 2019). This observation highlights the complexity of interactions between primary biogenic emissions and secondary aerosol formation processes occurring during the Quiet NPF process.

2.2 Growth and Formation Rates Associated with Quiet NPF

To characterize Quiet NPF, we calculated its characteristic GR based on the median PNSD during non-event days through the appearance time method within the diameter range of 10–25 nm (Lehtipalo et al., 2014; Kulmala et al., 2022). We identified the time when the particle concentration reached the closest to 50% of its maximum value within each diameter bin and applied linear regression to these time-diameter points to obtain the GR, as shown in **Fig. 2**. The resulting linear fit yielded a statistically significant GR of 2.3 ± 0.1 nm h^{-1} (R^2 = 0.95, p-value < 0.01). This GR is lower compared to previously reported rates for classical growth events in the Amazon boundary layer (4–6 nm h^{-1}; Rizzo et al., 2018; Franco et al., 2022) and on the lower range of the typical GR observed at continental sites worldwide (2–7 nm h^{-1}; Kerminen et al., 2018). Even when compared with lower nighttime GRs observed in the Amazon boundary layer (4 nm h^{-1}; Franco et al., 2022), our obtained GR remains approximately twofold lower.

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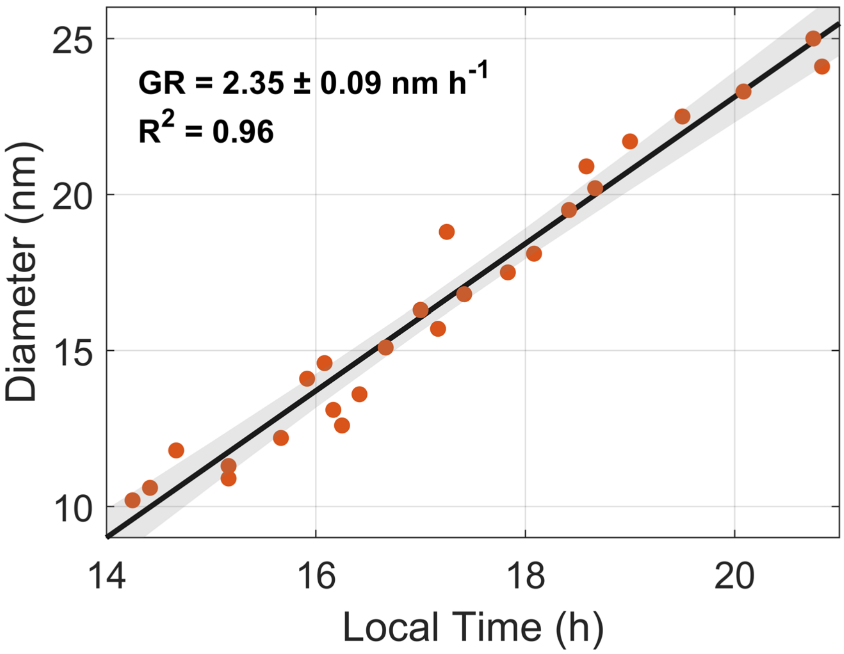

Figure 2. Linear regression of particle growth rate (GR) using the appearance time method. Points represent the time when particle concentration in each diameter bin (10–25 nm) reached 50% of its daily maximum. The solid line indicates the statistically significant linear regression (GR = 2.35 ± 0.09 nm h^{-1}, p-value < 0.01), with the shaded area representing the 95% confidence interval.

We subsequently calculated the formation rates of 10 nm particles (J_{10}) at 30-minute intervals on both event and non-event days, applying the aerosol population balance equation (Equation 1). The 10–25 nm diameter range encompasses particles that may be formed in the upper troposphere and transported to the boundary layer. This vertical transport effect is known to influence event days significantly but is minimal on non-event days, consistent with predominantly positive $\Delta\theta_e$ values that indicate minimal downdraft contributions.

For event days, individual GR values were calculated per event, as indicated in Section 2. For non-event days, the obtained single representative GR value (2.3 nm h^{-1}) was uniformly applied. While this is a simplification — since growth rates could vary with precursor gas availability and properties (Kirkby et al., 2023) — the GR for non-event days can only be reliably obtained from long-term averages. Previous studies have shown that, despite substantial fluctuations in precursor concentrations, GR tends to vary only slightly within a given environmental condition (Kulmala et al., 2022b), which justifies this approach and aligns with the methodology of other studies (Kulmala et al., 2022a; Aliaga et al., 2023; Chen et al., 2023).

Using this approach, **Fig. 3a** and **3b** present the median diurnal cycles of J_{10} for both event and non-event days, with individual contributions from each term in the balance equation explicitly shown. The *dN/dt* term reflects temporal variability in particle number, the "Coag." term accounts for particles lost to coagulation into larger particles (>25 nm), the

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"Growth" term represents condensational growth, and "total" corresponds to J_{10}—the sum of all terms. As expected for Quiet NPF, J_{10} during non-event days is substantially lower than during event days, in agreement with previous observations (Kulmala et al., 2022a). Notably, the coagulation term is proportionally larger on non-event days, indicating that slower growth rates increase the likelihood of newly formed particles being lost to coagulation. The median total J_{10} during the middle of non-event days is slightly negative, which may result from unaccounted particle losses, such as deposition onto particles larger than the upper detection limit of the SMPS (420 nm) or vertical dispersion. Overall, the calculated formation rates for the Amazon are lower than those reported in other regions (Kirkby et al., 2023), consistent with the region's typically low concentrations of sub-50 nm particles.

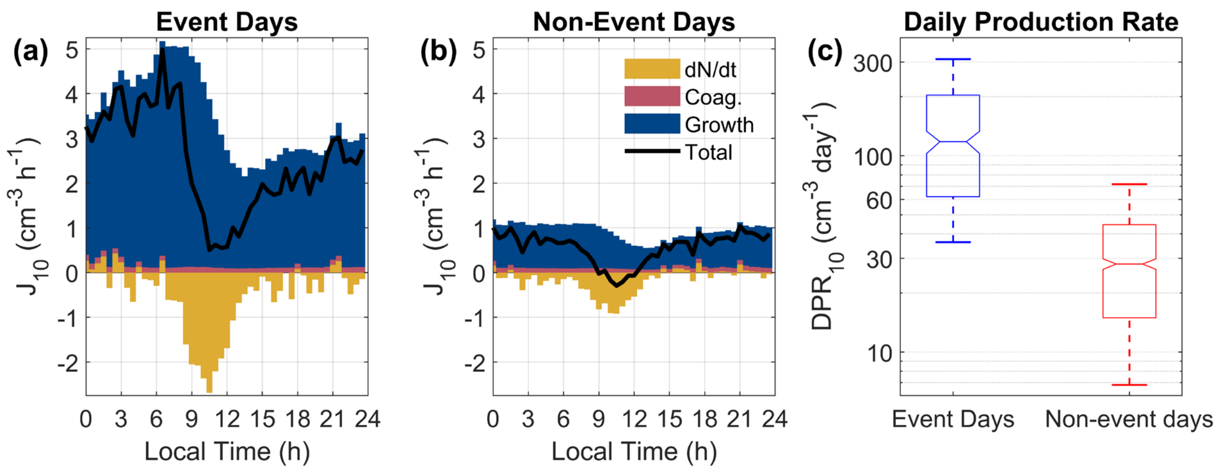

Figure 3. Formation and production rates of 10 nm particles (J_{10}) during event and non-event days at ATTO. Panels (a) and (b) depict the median diurnal cycle of J_{10} on event and non-event days, respectively, partitioned into individual terms from the aerosol balance equation: particle number concentration variation (*dN/dt*), coagulation sink (Coag.), and growth. Panel (c) compares daily production rates of particles (10–25 nm) for event (blue) and non-event (red) days. Boxes indicate the interquartile range (25th–75th percentiles), and whiskers represent the 10th and 90th percentiles.

Integrating J_{10} values over the entire day provided the daily particle production rates within the 10–25 nm range (DPR_{10}), presented in **Fig. 3c**. Median daily production rates (interquartile range) were 117 (61–204) cm^{-3} day^{-1} for event days and 28 (15–45) cm^{-3} day^{-1} for non-event days. For comparison, Kulmala et al. (2022a) reported a daily production rate of 286 cm^{-3} day^{-1} for particles between 6–25 nm during non-event days in Hyytiälä. Despite the narrower size range analyzed here, our observed lower production rates demonstrate the reduced particle formation capacity characteristic of the Amazonian boundary layer.

Considering the higher frequency of non-event days (approximately 77%) compared to event days (23%), we estimate that Quiet NPF accounts for approximately 45% of the observed 10–25 nm particles during the wet season, highlighting its significant and persistent role in nanoparticle production in the Amazon boundary layer. Although the absence of rain-related downdrafts and classical NPF events does not guarantee that Quiet NPF is active every non-event day, we use the mean characteristics of non-event days to estimate its typical contribution. This approach is consistent with recent studies

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suggesting that new particle formation occurs across a spectrum of intensities, from prominent events to more subtle, persistent processes (Kulmala et al., 2022a; Aliaga et al., 2023).

4 Discussions and conclusions

This study identified a previously unrecognized mechanism of new particle formation in the Amazon, termed Quiet NPF, which occurs in different locations within the Amazonian boundary layer during the wet season. Our findings, in line with the proposal by Kulmala et al. (2024), demonstrate that NPF is not restricted to intense and easily identifiable growth episodes. By analysing a decade-long dataset of particle number size distributions and systematically aggregating days lacking clear nucleation signatures, we were able to characterize this subtle yet significant aerosol source. Quiet NPF fundamentally differs from the rainfall/downdraft-related events in the Amazon, as it is characterized by substantially lower growth rates (~2.4 nm h^{-1}) and particle formation rates (~1 cm^{-3} h^{-1}). Nevertheless, due to its higher frequency, Quiet NPF makes a considerable contribution to the population of 10–25 nm particles, with an estimated daily production rate of approximately 28 cm^{-3} day^{-1}. While this rate is lower than the 117 cm^{-3} day^{-1} observed during Amazonian banana event days, Quiet NPF accounts for roughly 45% of sub-25 nm particles during the wet season, highlighting its essential role in sustaining the Amazonian aerosol population.

An intriguing difference emerges between the Amazonian banana events driven by downdrafts and precipitation, which predominantly occur during the daytime, with maximum J_{10} after sunrise, and Quiet NPF, characterized by maximum particle concentrations and J_{10} observed at night. A plausible explanation for this nocturnal enhancement includes reduced nighttime accumulation-mode particle concentrations, which decrease the coagulation and condensation sinks for small particles and their precursors. Additionally, nighttime atmospheric conditions involve a significant reduction in the isoprene-to-monoterpenes ratio (Yáñez-Serrano et al., 2015, 2020), which potentially alleviates isoprene's known suppressive effects on nucleation (Heinritzi et al., 2020).

The initial growth stage of Quiet NPF likely commences during the daytime, as indicated by a concentration peak of ~10 nm particles around 18:00. Daytime oxidation of VOCs, molecular clustering, and the formation of extremely low-volatility and ultra-low-volatility organic compounds (ELVOCs and ULVOCs) are presumed to initiate particle nucleation and early growth (Mohr et al., 2019; Schervish & Donahue, 2020). However, the observed slow growth rates suggest relatively lower concentrations of ELVOCs and ULVOCs within the Amazon BL, potentially linked to isoprene-related suppression mechanisms (Heinritzi et al., 2020; Curtius et al., 2024). Instead, the subsequent growth to larger Aitken-mode sizes may rely predominantly on the condensation of more abundant higher-volatility organic compounds (Liu et al., 2022; Curtius et al., 2024). Therefore, a plausible scenario involves initial slow nucleation and growth driven by limited ELVOC/ULVOC levels, transitioning into faster growth facilitated by higher-volatility compounds.

The pronounced differences in growth and formation rates, along with the temporal patterns distinguishing Quiet NPF from rainfall/downdraft-related events, point to distinct chemical mechanisms within the boundary layer. Quiet NPF also differs

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from nucleation in the upper troposphere, where isoprene-derived organonitrates drive particle formation (Curtius et al., 2024; Zha et al., 2024). At ground-level temperatures, organonitrates formed from isoprene oxidation are not expected to contribute significantly to nucleation or the initial stages of particle growth (Heinritzi et al., 2020; Curtius et al., 2024). Moreover, ozone enhancements commonly observed during downdraft events (Machado et al., 2021, 2024) are unlikely to influence Quiet NPF, given the consistently lower ozone concentrations measured in the pristine Amazon boundary layer during periods without downdrafts.

In summary, this study highlights a previously undocumented, frequent NPF mechanism within the Amazonian boundary layer, distinct from nucleation and growth events associated with convective downdrafts and precipitation. Our findings underscore the complexity of aerosol dynamics in this unique environment and emphasize the necessity of future research focused on elucidating the interplay between chemical precursors and meteorological factors. Despite recent advances in understanding the aerosol secondary production within the Amazonian atmosphere, our study reveals a potential New Particle Formation mechanism that might be underrepresented, warranting future model evaluation. Future studies should incorporate long-term measurements of sub-10 nm particles and detailed analyses of low-volatility precursor compositions, further clarifying the distinct processes contributing to aerosol formation in the Amazon.

Appendix A - Instrumentation and Data Processing

This study was conducted at the ATTO site, situated in a remote, forested area of the Central Amazon, approximately 150 km northeast of Manaus, Brazil. This region is characterized by comparatively low aerosol concentrations during the wet season, making it an ideal natural laboratory to investigate the pristine aerosol life cycle (Artaxo et al., 2013, 2022). A comprehensive site description is available in Andreae et al. (2015). We analyzed a decade of measurements spanning 2014 to 2023, focusing exclusively on the wet season, defined as January to May.

Meteorological parameters, including pressure, temperature, relative humidity, and precipitation, were measured using a Barometer (PTB101, Vaisala), a Thermo-Hygrometer (IAK I-Series, Galltec-Mela), and a rain gauge (TB4, Hyquest Solutions) installed 81 m above ground level**.** To evaluate the influence of convective downdrafts on particle formation and/or transport, we calculated the potential equivalent temperature (θ_e), a conservative thermodynamic variable that decreases with altitude. Sharp negative anomalies in θ_e are used to identify downdraft activity (Gerken et al., 2016; Dias-Junior et al., 2017). To remove the effect of diurnal variability, we calculated the diurnal anomaly of θ_e, defined as the deviation of instantaneous θ_e from its median value at the same hour ($\Delta\theta_e$). Rather than directly identifying individual downdrafts, we used $\Delta\theta_e$ statistics to compare typical downdraft behaviour and frequency across different classes of days.

Aerosol particle number size distributions (PNSD) were measured with Scanning Mobility Particle Sizers (SMPS; TSI classifiers 3080/3082 coupled with CPC models 3772/3750) placed inside the ATTO laboratory containers and sampling air through inlet lines from a height of 60 meters above ground, which corresponds to approximately 25 meters above the forest canopy. The SMPS provided online measurements of PNSD every 5 minutes for particle diameters ranging from 10.2 to 420

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nm, with a 61% data coverage rate during wet seasons from 2014 to 2023. Detailed information on the design of the sample air inlet and dryer can be found elsewhere (Pöhlker et al., 2016).

To ensure data quality, measurements were corrected for diffusional, sedimentation, and inertial losses following Von der Weiden et al. (2009). The data were then smoothed using a two-dimensional mean filter, averaging over a 90-minute time window and five diameter bins, as recommended by Kulmala et al. (2012). All concentrations were converted to standard temperature and pressure conditions (273.15 K, 1013.25 hPa) for consistency.

Appendix B - Identification and characterization of growth events

Growth events were identified using criteria from Franco et al. (2022), which in turn are based on modifications to the method of Kulmala et al. (2012). Events were defined by the appearance of a distinct mode with a peak diameter between 10 and 40 nm, persisting for at least one hour, and exhibiting a positive shift in modal diameter. In comparison to "classical NPF events", this allows for the inclusion of "Amazonian Banana" episodes, where initial particle growth may not be local. Across the 2014–2023 wet seasons, 212 event days and 717 non-event days were identified, yielding a growth event frequency of 23%, consistent with Franco et al. (2022). Examples of both event and non-event days are shown in **Fig. B1**.

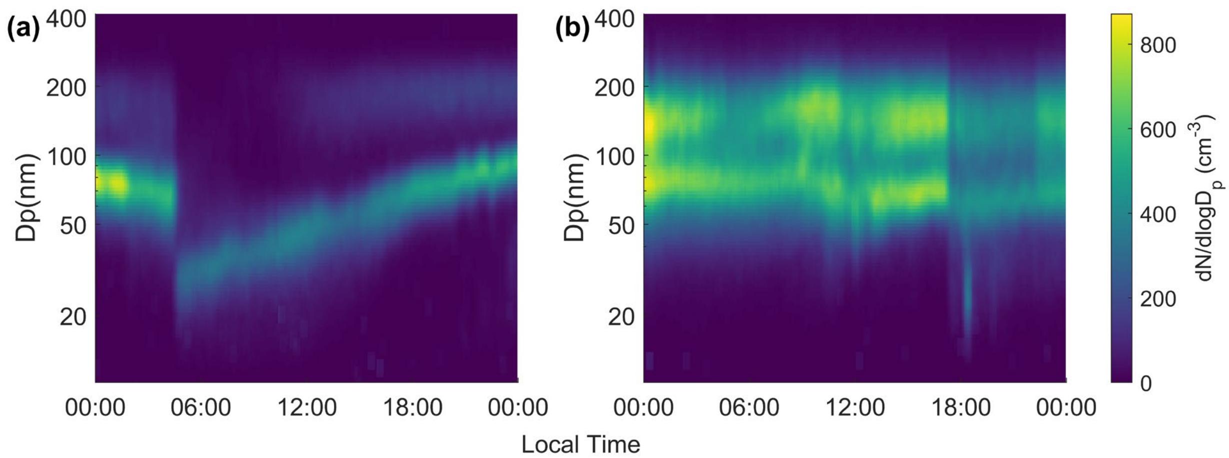

Figure B1. Particle number size distribution during (a) a growth event day (09-Apr-2022) and (b) a non-event day (27-Apr-2022).

For characterising events, we followed Franco et al. (2022), employing multi-lognormal fits to the PNSD, with three modes: sub-50 nm (10–50 nm), Aitken (50–100 nm), and accumulation (100–420 nm). Fits with $R^2 > 0.6$ and p-value < 0.05 were included. Growth rates (**GR**) for the events were calculated by linear regression of time versus geometric mean diameter in the sub-50 nm mode. Particle formation rates at 10 nm (J_{10}) were calculated using the aerosol population balance equation (Kulmala et al., 2012):

$$J_{10} = \frac{dN_{10-25}}{dt} + CoagS \times N_{10-25} + \frac{GR}{\Delta d_p} \times N_{10-25} \quad (1)$$

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where $N_{10\text{-}25}$ is the concentration of particles 10–25 nm, $dN_{10\text{-}25}/dt$ its time derivative, *CoagS* the coagulation sink calculated from the size distribution, based on coagulation coefficients for each particle size (Kerminen et al., 2001; Seinfeld & Pandis, 2016), and Δd_p the size interval (25–10 nm). This size range focuses our analysis on recently nucleated particles, minimising primary source contributions.

Appendix C - Analysis of Non-Event Days and Quiet NPF

To better visualize sub-50 nm particle variability during non-event days, we calculated the diurnal median PNSD and normalized it using the method of Kulmala et al. (2022a), scaling each diameter bin's number concentration from 0 (minimum) to 1 (maximum) over the period of a day. This approach emphasises daily maxima and minima for each size class, regardless of absolute concentration, and highlights the evolution of particle populations even when absolute changes are subtle.

For the growth rate calculation on non-event days, the lognormal fit of the sub-50 nm mode was ill-defined due to low concentrations. Therefore, the appearance time method (Lehtipalo et al., 2014) was employed. Specifically, for diameters 10–25 nm, we identified the time each bin reached 50% of its daily maximum, then performed linear regression on these time-diameter pairs to estimate the GR. This method is well-suited for detecting gradual or subtle growth when lognormal fits are not applicable.

Data availability

Data will be openly available at Edmond, the Open Research Data Repository of the Max Planck Society, at the time of publication. Currently, data is temporarily available at http://ftp.lfa.if.usp.br/ftp/public/Temp/Edmond_Meller2025_Paper/.

Author Contribution

B. B. Meller conceived the study, processed data, performed the analyses, and prepared the manuscript. M. A. Franco and R. Valiati processed data and contributed to the analysis and interpretation. C. Pöhlker, F. Ditas, L. A. Kremper, S. S. Raj, C. Q. Dias-Júnior, and F. A. F. D'Oliveira carried out field measurements at ATTO and processed. L. V. Rizzo, C. Pöhlker, L. A. T. Machado, U. Pöschl, and P. Artaxo contributed to supervision, project administration, and funding acquisition. All authors contributed to the discussion of results and to reviewing and editing the manuscript.

Competing Interests

Some authors are members of the editorial board of the journal Atmospheric Chemistry and Physics.

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