

1 High Frequency of Urban New Particle Formation on the Tibetan 2 Plateau: Quantifying Formation Rates, Growth Rates, and CCN 3 Production

4 Qiqi Mo¹, Longjie Wen^{1,2}, Gang Zhao^{1,3*}, Chunxiang Ye^{4*}, Jie Sun¹, Weili Lin^{1,5}, Fengjun Shen¹, Tong
5 Liu¹, Yicheng Gao¹, Yi Chen⁴, Tiantian Zhang¹, Tong Zhu⁴

6 1Key Laboratory of Ecology and Environment in Minority Areas, Minzu University of China, National Ethnic Affairs
7 Commission, Beijing 100081, China

8 2School of Ecology and Environment, College of Intelligence, Harbin Institute of Technology (Shenzhen), Shenzhen,
9 518055, China

10 3Key Laboratory of Biodiversity and Environment on the Qinghai-Tibet Plateau, Ministry of Education, Xizang University,
11 Lhasa 850000, China

12 4SKL-ESPC & SEPCL-AERM, College of Environmental Sciences and Engineering, Institute of Tibetan Plateau, and
13 Center for Environment and Health, Peking University, Beijing, China

14 5Institute of National Security, Minzu University of China, Beijing, 100081, China

15 Correspondence to: Gang Zhao (gangz@muc.edu.cn) and Chunxiang Ye (c.ye@pku.edu.cn)

16 Abstract

17 New particle formation (NPF) strongly influences aerosol number size distributions and cloud condensation nuclei (CCN),
18 yet its characteristics and climatic relevance in high-altitude urban environments over the Tibetan Plateau (TP) remain
19 poorly constrained. We conducted in situ observations at Tibet University (TU) in Lhasa during the spring and autumn
20 observation periods. NPF event frequencies were 86.2 % during the autumn observation period and 62.1 % during the spring
21 observation period. Observation days were classified as NPF, Undefined, or Non-Event days based on PNSD evolution,
22 supported by size-segregated particle number concentrations and particle growth rates. Observation-period comparisons
23 indicate clear differences in the factors associated with NPF: NPF during the autumn observation period may have been
24 favored by greater sulfur-precursor availability, whereas no single dominant controlling factor could be identified during the
25 spring observation period. Estimated CCN concentrations were higher on NPF days (mean $\pm$ standard deviation: (2.3 ± 1.5)
26 $\times 10^3 \text{ cm}^{-3}$; median: $1.9 \times 10^3 \text{ cm}^{-3}$). Corresponding mean $\pm$ standard deviation and median values were $(0.9 \pm 0.4) \times$
27 10^3 and $0.81 \times 10^3 \text{ cm}^{-3}$ on Undefined days and $(1.3 \pm 0.7) \times 10^3$ and $1.1 \times 10^3 \text{ cm}^{-3}$ on Non-Event days,
28 respectively. The impact of NPF on CCN depends not only on nucleation, but also on the continued growth and survival of
29 newly formed particles. This study provides new insights into urban NPF characteristics and its potential contribution to
30 CCN on the TP, improving our understanding of aerosol–climate interactions in high-altitude urban environments.

31 1 Introduction

32 The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) highlights that the aerosol climatic
33 effect is a major source of uncertainty in climate change assessment, primarily attributed to the spatio-temporal variability of
34 aerosol concentration and size distribution (Arias et al., 2021). New Particle Formation (NPF) and subsequent particle
35 growth significantly alter aerosol concentration, size distribution, and Cloud Condensation Nuclei (CCN) concentration
36 (Hong et al., 2023). Endowed with unique geographical and atmospheric conditions, the Tibetan Plateau (TP) hosts aerosols
37 that are prone to long-distance transport. This capability allows TP aerosols to modify atmospheric concentration and cloud
38 properties along their path more readily than those in low-altitude regions, thereby impacting both regional atmospheric
39 environment and global climate (Hu et al., 2024). Thus, in-depth exploration of NPF patterns over the TP is crucial for
40 accurately evaluating TP aerosol impact on the global atmosphere and climate.

41 NPF has also been frequently observed at high-altitude mountain and free-tropospheric sites outside the TP, where
42 mountain-valley circulation, boundary-layer transport, and low-temperature conditions can strongly influence precursor
43 supply and particle formation. At the Nepal Climate Observatory–Pyramid in the Himalayas, frequent NPF was previously
44 observed under the influence of valley winds (Venzac et al., 2008). More recent molecular-level observations at the same
45 site showed that up-valley transport supplied gaseous precursors that were oxidized into low-volatility organic compounds,
46 producing new biogenic particles that could subsequently enter the free troposphere (Bianchi et al., 2021). At the Chacaltaya
47 high-altitude station in Bolivia, NPF and subsequent particle growth produced substantial enhancements in CCN-relevant
48 particle concentrations under both boundary-layer-influenced and free-tropospheric conditions (Rose et al., 2017). These
49 studies demonstrate that high-altitude NPF can be strongly affected by vertical transport and organic precursor chemistry. In
50 contrast, Lhasa represents a high-altitude urban environment influenced by traffic, combustion, construction activities, and
51 elevated anthropogenic gaseous precursors. It therefore provides an opportunity to investigate how urban emissions modify
52 mountain NPF processes that have previously been studied mainly at remote background sites.

53 Research on NPF in the TP background atmosphere is extensive, leading to a comprehensive understanding of its
54 environmental and climatic effects. For instance, a study at the National Atmospheric Background Monitoring Sub-station
55 on Moshi Daban Mountain (3295 m a.s.l.) in Menyuan, Qinghai Province (Gao et al., 2025), found that NPF events occurred
56 on approximately 80 % of the observation days. These events typically started in the morning, with aerosol particle sizes
57 rapidly growing from approximately 5 nm to 150 nm, exhibiting the characteristic "banana-shape" curve. Intensive
58 measurements at Nam Co station (4730 m a.s.l.) in the central TP (Tang et al., 2023) explored NPF frequency and
59 mechanisms, revealing significant seasonal differences: approximately 15 % in the pre-monsoon season but up to 80 %
60 during the summer monsoon. Comprehensive analysis of the CS, gaseous precursors, and meteorological factors, combined
61 with SO₂ and Volatile Organic Compounds (VOCs) simulations, concluded that organics-involved condensation is the
62 dominant NPF mechanism, with CS and gaseous sulfuric acid having negligible influence. Furthermore, the high NPF
63 frequency during the summer monsoon season may be closely linked to frequent southerly and south-westerly airflow.

64 Focusing on the south-eastern TP (Lai et al., 2024), research investigated NPF jointly driven by anthropogenic and biogenic
65 factors. Using field measurements and a chemical transport model, they found frequent NPF events on clear-sky days during
66 the pre-monsoon season, contributing significantly to CCN concentration. Observations confirmed that Highly Oxygenated
67 Organic Molecules (HOMs) from monoterpene oxidation participate in the nucleation process in this region. Liu et al. (2024)
68 further showed that the frequent NPF at high-altitude sites in the south-eastern TP is mainly driven by HOMs, including
69 products from monoterpene, and unexpectedly, sesquiterpenes and diterpenes oxidation. Moreover, anthropogenic NO_x
70 emissions were found to play a crucial regulatory role in particle nucleation. Overall, NPF frequency is high in the TP
71 background atmosphere, and its formation is closely related to temperature, relative humidity, and chemical precursor
72 concentrations.

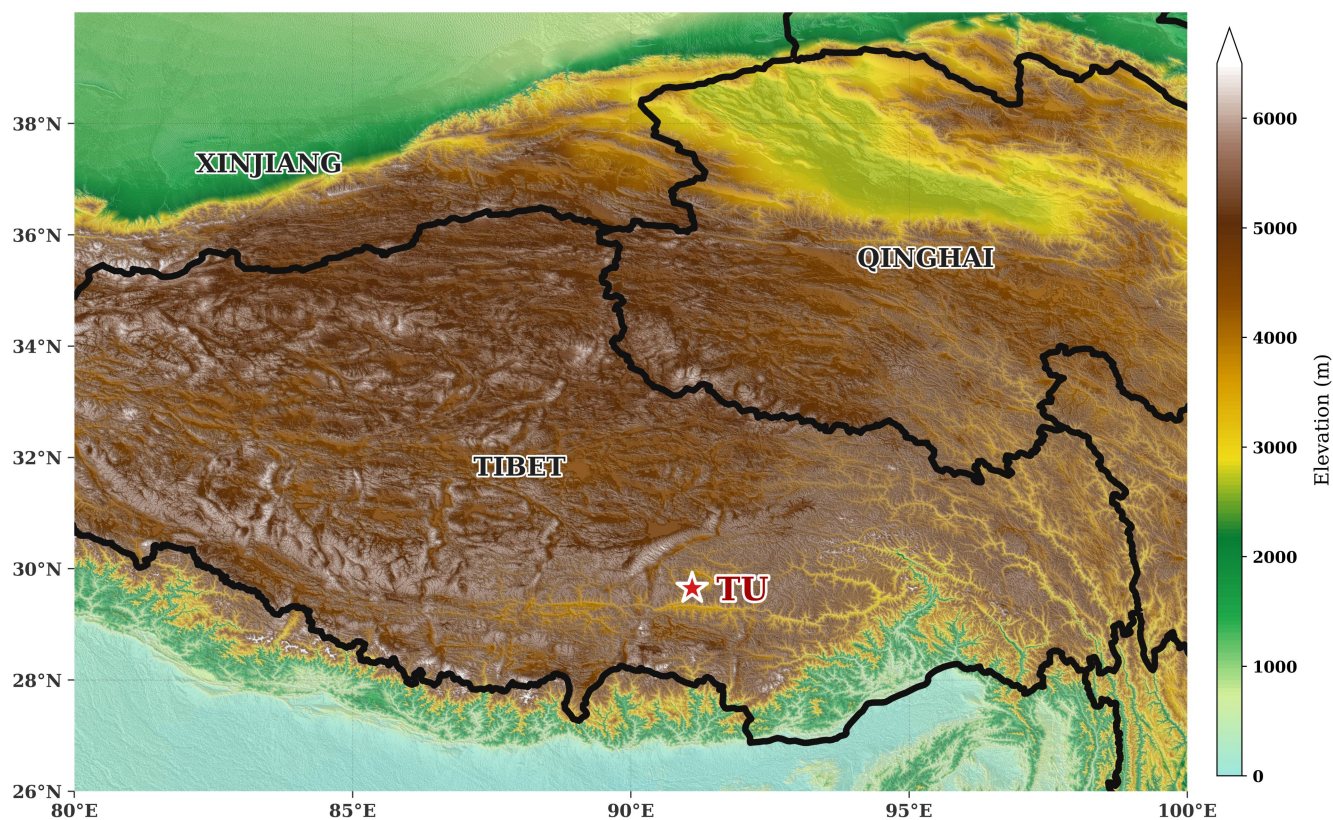
73 Aerosols generated by NPF in the TP background atmosphere can contribute up to half of the total atmospheric aerosol
74 number concentration and significantly enhance CCN concentration. A study at the world's highest station, Chacaltaya (Rose
75 et al., 2017), analysed 61 % of NPF events, finding they led to increased CCN number concentration, with the probability
76 reaching 79 % during the wet season due to faster particle growth. The NPF impact on CCN concentration varies seasonally,
77 causing CCN to increase by a factor of 1.54 and 1.36 in spring and winter, respectively. During the summer monsoon season,
78 at a supersaturation of 1.2 %, aerosol number concentration and CCN concentration surged by a factor of 2 and 0.6,
79 respectively, compared to the pre-monsoon season. Furthermore, considering that small particles formed during NPF may
80 continue to grow to CCN activation size over several days, the potential CCN number during the monsoon season may far
81 exceed instantaneous local measurements (Tang et al., 2023). Comparative observations by Shang et al. (2022) indicated that
82 the NPF contribution to total aerosol and CCN concentrations is more significant in the clean atmosphere than that of the
83 polluted atmosphere.

84 Despite the extensive work summarized above, our understanding of new-particle formation over the TP remains strongly
85 biased toward remote background sites. The urban TP atmosphere—characterised by markedly stronger primary emissions
86 and elevated concentrations of both SO_2 and NO_x —has, so far, received no systematic exploration of its NPF characteristics,
87 governing mechanisms, or quantitative contribution to CCN. This knowledge gap hampers the accurate representation of
88 aerosol sources in regional climate models and precludes a full assessment of the role of urban NPF over the TP in
89 continental CCN budgets. To fill this gap, we carried out seasonal-scale particle number size distribution (PNSD)
90 measurements in Lhasa (3650 m a.s.l.), a high-altitude urban environment on the Tibetan Plateau, during the spring and
91 autumn observation periods. The specific aims are (i) to establish an event classification and to quantify the frequency and
92 intensity of urban NPF, (ii) to elucidate the seasonal differences in precursor–meteorology interactions driving NPF, and (iii)
93 to evaluate the instantaneous and seasonal enhancement of CCN concentrations attributable to newly formed particles at the
94 TP urban environment. The observational methodology is described in Section 2, results and discussions are presented in
95 Section 3, and conclusions together with implications for aerosol–climate interactions are summarized in the last Section.

96 2 Methods

97 2.1 Sampling sites

98 As shown in Fig. 1, the study site is located at Tibet University (TU, 29 °38 ' N, 91 °10 ' E; 3650 m a.s.l.) in Lhasa,
99 which lies in the south-central TP. Lhasa serves as the capital of the Tibet Autonomous Region and its political, economic,
100 and cultural hub. As one of the largest urban centers on the TP, it is a typical high-altitude city where aerosols are
101 predominantly driven by local sources, including traffic emissions, residential coal/biomass combustion, construction
102 activities, and dust resuspension (Zhao et al., 2022). Traffic-related particle concentrations can exhibit pronounced spatial
103 and temporal heterogeneity within complex urban environments, which may not be fully captured by fixed-site
104 measurements (Yeganeh et al., 2026). This spatial heterogeneity should therefore be considered when interpreting the
105 influence of local urban emissions at the TU site. The site is situated in a broad river valley surrounded by mountains with
106 elevations up to 5500 m a.s.l. Its climate is strongly influenced by the Asian Summer Monsoon and the East Asian Winter
107 Monsoon, with spring and autumn functioning as transitional seasons between these two climate systems (Li et al., 2025). In
108 situ measurements were conducted during two periods: the autumn observation period (9 October–10 November 2024) and
109 the spring observation period (25 March–22 April 2025).



111 **Figure 1: Regional topography and location of the Tibet University (TU) observation site in Lhasa, Tibet Autonomous Region,**
112 **China. Color shading denotes elevation above sea level (m), black lines indicate provincial-level administrative boundaries, and the**
113 **red star marks the TU observation site.**

114 **2.2 Instrumentation**

115 In this study, a comprehensive Scanning Mobility Particle Sizer (SMPS) system was employed to measure the PNSD from 3
116 to 800 nm with a 5-minute time resolution. This system consisted of two separate instruments from TSI Inc. A nanoparticle
117 SMPS (TSI, Model 3087) was used to measure particles in the size range of 3 to 40 nm, while a standard SMPS (TSI, Model
118 3080) measured particles from 20 to 800 nm. The two datasets were then merged to create a complete and continuous PNSD.
119 To ensure consistent and accurate measurements, the instruments were housed in a temperature-controlled container
120 maintained at 25 °C. This setup was located on the rooftop of a campus building, with the aerosol inlet positioned
121 approximately 20 meters above ground level. This elevated sampling height was chosen to minimize the influence of
122 localized ground-level emission sources like traffic exhaust and suspended road dust. Furthermore, a silicon diffusion dryer
123 was placed upstream of the SMPSs to reduce the relative humidity of the sampled air to below 40 %, preventing particle
124 growth from water vapour condensation. Ambient aerosols were sampled through a short, conductive tube with minimal
125 bends to reduce size-dependent diffusion losses. All SMPS data underwent rigorous corrections for these diffusion losses
126 and for multiple charging effects to ensure the reliability of the measured particle number concentrations. We also utilized
127 meteorological data from an on-site automatic weather station, which provided essential parameters including temperature
128 (T), relative humidity (RH), wind speed (WS), wind direction (WD), Sulfur Dioxide (SO₂), Nitrogen Dioxide (NO₂), and
129 Ozone (O₃) for a comprehensive analysis of the atmospheric conditions. Because gaseous H₂SO₄ was not directly measured,
130 a relative H₂SO₄-related photochemical proxy was additionally calculated for periods with available spectral measurements
131 during the autumn observation period; the calculation procedure and associated limitations are described in Sect. S1.

132 **2.3 Calculation of variables characterizing new particle formation**

133 The Condensation Sink (CS, unit: s⁻¹) is utilized in this study as a core parameter to quantify the regulating effect of pre-
134 existing aerosols on condensable vapors (Kerminen et al., 2018; Wu et al., 2021). Its calculation is based on the kinetic
135 theory of dilute gases and assumes sulfuric acid (H₂SO₄) as the characteristic condensable substance (Dal Maso, 2005). The
136 calculation process utilizes measured PNSD data and incorporates the influence of ambient temperature (T) and pressure (P).
137 First, the diffusion coefficient of sulfuric acid vapor in the air ($D_{x, \text{air}}$) is calculated using an empirical formula based on T and
138 P. Subsequently, the mean free path of the condensable vapor (λ) is calculated using the molar mass of sulfuric acid ($M_x =$
139 98.08 g/mol). Based on λ and the size-resolved particle radius (R_i), the Knudsen number ($Kn_i = \lambda/R_i$) is determined. To
140 correct the condensation rate from the continuous regime to the transition and free molecular regimes, the transition regime
141 correction factor (β) is introduced (Dinoi et al., 2021):

$$\beta = \frac{Kn + 1}{0.377Kn + 1 + \frac{4}{3\alpha}(Kn^2 + Kn)} \quad (1)$$

Here, the sticking coefficient (α) is set to 1.0. Finally, the size-resolved condensation sink (CSi) is determined by $4\pi \cdot D_{x,air} \cdot R_i \cdot \beta_i \cdot n_i$, and the total CS value is quantitatively calculated by numerically integrating CSi over all particle size ranges.

$$CS = 2\pi D \int_0^\infty d_p \beta_m(d_p) \times n(d_p) dd_p = 2\pi D \sum_i \beta_i d_{pi} N_i \quad (2)$$

The Coagulation Sink (CoagS, unit: s^{-1}) is another key parameter in atmospheric aerosol dynamics, quantifying the efficiency of pre-existing particles (scavenger particles) in removing specific size-range target particles from the system via the coagulation mechanism (Kulmala et al., 2001). Similar to CS, CoagS is calculated through PNSD integration.

$$CoagS_{d_p} = \int K(d_p, d_{p'}) n(d_{p'}) dd_{p'} \cong \sum_{d_{p'}=d_p}^{d_{p'}=\max} K(d_p, d_{p'}) N_{d_{p'}} \quad (3)$$

GR, defined as the rate at which the geometric mean diameter of nucleation mode particles increases from dp_1 to dp_2 , was calculated using the procedure outlined by (Kulmala et al., 2012).

$$GR = \frac{\Delta d_p}{\Delta t} = \frac{d_{p2} - d_{p1}}{t_2 - t_1} \quad (4)$$

To quantify the intensity of NPF events, we calculated the particle formation rate J (i.e., the rate of aerosol particle formation at a specific size) following the method described by (Baalbaki et al., 2021), which is derived from rearranging the equation governing the time evolution of particle number concentration (Kulmala et al., 2012). Specifically, J was computed for two size bins (dp): 3 nm (J_3), and 7 nm (J_7), with the upper size limits of the corresponding bins set to 7 nm and 20 nm, respectively. The growth rate term in the equation (Eq. 5) was defined as the average of GR measurements for total particles; this GR value was assumed constant during NPF events and set to zero outside the event duration or in non-event periods. The formation rate J_{dp} is expressed as:

$$J_{d_p} = \frac{dN_{d_p}}{dt} + CoagS_{d_p} \cdot N_{d_p} + \frac{GR}{\Delta d_p} \cdot N_{d_p} \quad (5)$$

CCN concentration is quantitatively calculated based on κ -Köhler theory (Petters and Kreidenweis, 2007). This method aims to determine the number of particles that can be activated at a specific supersaturation (S).

$$A = \frac{4\sigma_{s/a} M_w}{RT\rho_w} \quad (6)$$

$$\kappa = \frac{4A^3}{27D_c^3 \ln^2 S_c} \quad (7)$$

In Eqs. (6) and (7), D_c is the critical dry particle diameter for CCN activation, S_c is the critical saturation ratio, and A is the Kelvin term. The parameter κ represents the influence of particle chemical composition on hygroscopicity and solution

168 water activity. $\sigma_{s/a}$ is the surface tension of water against air. M_w and ρ_w are the molar mass and density of water,
169 respectively. R is the universal gas constant, and T is the absolute temperature (K). In this study, κ and S were set to 0.12
170 and 1.2 %, respectively.

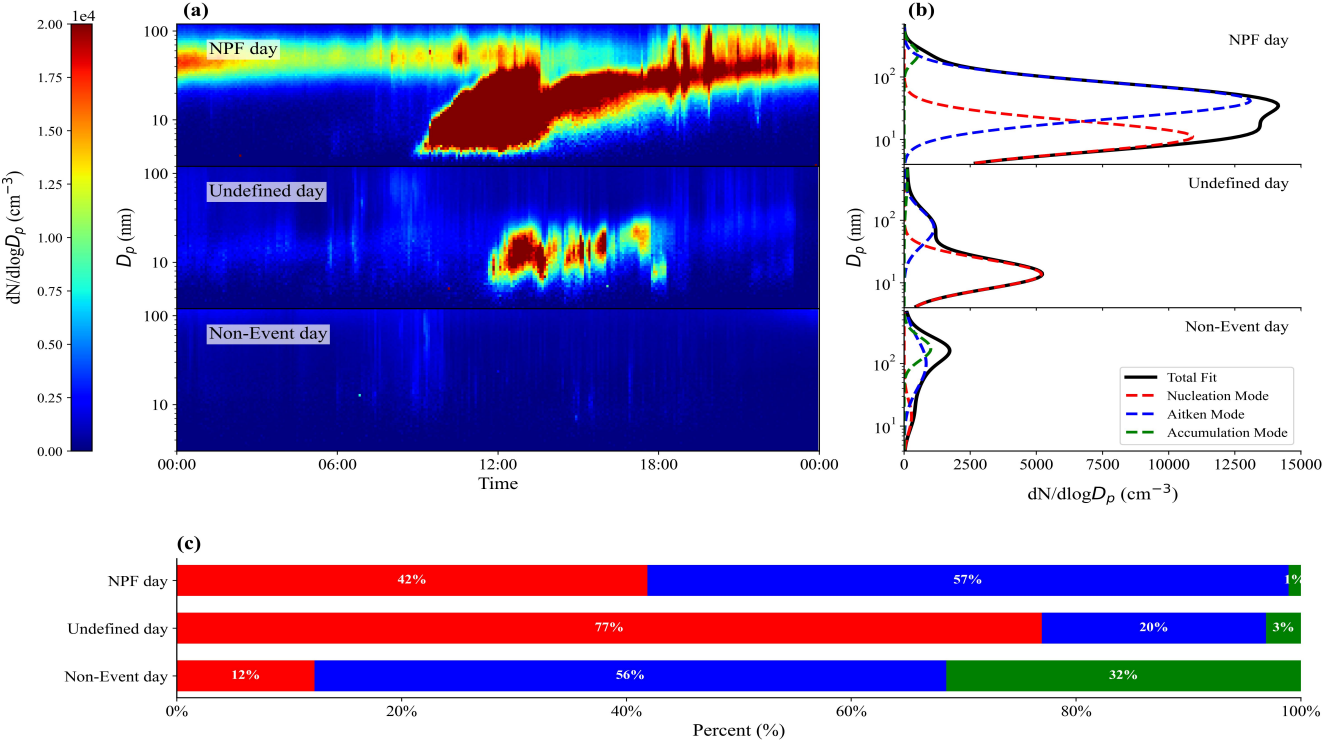
171 2.4 NPF Event Classification

172 In this study, atmospheric particles were divided into three diameter modes: the nucleation mode (< 25 nm), the Aitken
173 Mode (25–100 nm), and the accumulation mode (> 100 nm) (Wang et al., 2022; Hussein et al., 2020; Kalkavouras et al.,
174 2021; Shen et al., 2022). The classification followed the methodology proposed by Dal Maso et al. (2005), which has been
175 widely applied in previous NPF studies (Gao et al., 2025; Cramer et al., 2026; Lampilahti et al., 2025; Casans et al., 2025).
176 Based on visual inspection of the daily PNSD evolution, the observation days were classified as NPF days, Undefined days,
177 or Non-Event days. The classification was further supported by size-segregated particle number concentrations and
178 candidate particle growth rates.

179 NPF days were characterized by the appearance of a distinct new particle mode at small diameters followed by identifiable
180 growth toward larger sizes. Continuous growth throughout the entire day was not required because temporary interruptions
181 may result from changes in air masses, boundary-layer development, precursor availability, or missing measurements. All
182 remaining days were treated as non-NPF days and further divided into Undefined and Non-Event days. Undefined days
183 showed increases in small-particle concentrations or partial modal evolution, but the formation and growth patterns were too
184 weak, discontinuous, or ambiguous to be confidently classified as NPF. Non-Event days showed neither the distinct
185 appearance of a new particle mode nor its subsequent systematic growth. To improve the transparency of the classification,
186 the mean N_{3-25} and N_{25-100} concentrations during 09:00-18:00 local time and candidate GR_{7-20} values derived from continuous
187 growth trajectories within 07:00-18:00 were included as supporting metrics. These metrics were used to support the day-by-
188 day classification rather than as fixed classification thresholds. The revised classification, event timing, particle number
189 characteristics, and candidate GR_{7-20} values for individual observation days are provided in Table S1. Daily PNSD plots for
190 NPF, Undefined, and Non-Event days are presented in Figs. S1-S3. The former Class I and Class II categories were merged
191 into the NPF-day category for all main statistical analyses, while the original classification is retained in Table S1 only for
192 comparison and traceability.

193 Figure 2 presents representative dates for the NPF, Undefined, and Non-Event categories. Figure 2a shows their diurnal
194 PNSD evolution. On the NPF day, the number concentration of small particles began to increase at approximately 09:00
195 local time, followed by an identifiable shift of the particle mode from the nucleation mode toward the Aitken mode, forming
196 the characteristic “banana-shaped” pattern. On the Undefined day, the modal evolution was relatively weak, discontinuous,
197 or ambiguous. On the Non-Event day, no distinct formation of a new particle mode followed by systematic growth was
198 observed. Figure 2b shows the corresponding mean PNSD and modal fitting results for the nucleation mode, Aitken mode,
199 and accumulation mode. The NPF day was characterized by substantial contributions from both the nucleation mode and

200 Aitken mode, consistent with the formation and subsequent growth of newly formed particles. The Undefined day was
 201 dominated by particles in the nucleation mode but showed relatively limited development toward larger sizes, whereas the
 202 Non-Event day exhibited greater relative contributions from pre-existing particles in the Aitken mode and accumulation
 203 mode. Figure 2c shows the relative contributions of the three particle modes. On the NPF day, particles in the nucleation
 204 mode, Aitken mode, and accumulation mode contributed 42 %, 57 %, and 1 % of the total particle number concentration,
 205 respectively, consistent with the growth of newly formed particles toward the Aitken mode. On the Undefined day, the
 206 corresponding contributions were 77 %, 20 %, and 3 %, respectively, indicating that particles in the nucleation mode
 207 dominated but their subsequent growth remained limited or ambiguous. On the Non-Event day, the corresponding
 208 contributions were 12 %, 56 %, and 32 %, respectively, reflecting greater relative contributions from pre-existing particles in
 209 the Aitken mode and accumulation mode.



210
 211 **Figure 2: (a) Particle number size distribution evolution, (b) averaged modal fitting, and (c) relative number contributions for**
 212 **three day categories.**

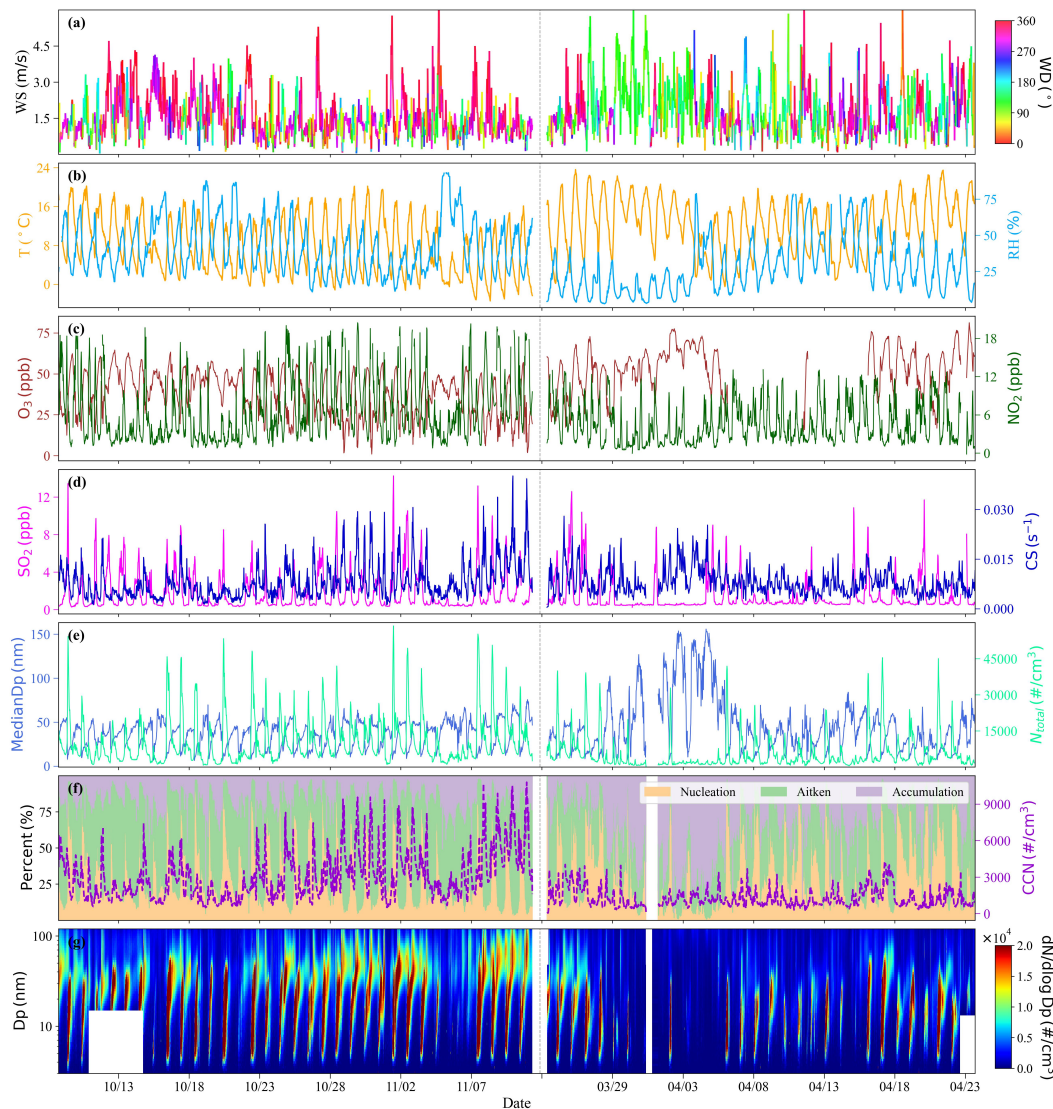
213 3 Results and discussion

214 3.1 Overview of the field observations

215 Meteorological conditions and gaseous pollutants exhibited strong short-term fluctuations and clear diurnal variability during
216 both measurement periods. As shown in Fig. 3a–b, WS, WD and RH varied substantially on synoptic and diurnal timescales.
217 The autumn observation period was characterized by higher RH (42 ± 18 %; median: 39 %) than the spring observation
218 period (28 ± 18 %; median: 23 %). Wind speeds were comparable between the two periods (arithmetic mean $\pm$ standard
219 deviation: 1.6 ± 0.9 and 1.9 ± 1.1 m s⁻¹; median: 1.4 and 1.7 m s⁻¹ for the autumn and spring observation periods,
220 respectively), indicating predominantly low-to-moderate ventilation conditions that may facilitate episodic accumulation of
221 precursors and aerosols. Figure 3c–d presents the temporal evolution of SO₂, CS, O₃, and NO₂. O₃ was generally higher
222 during the spring observation period ($52. \pm 14$ ppb; median: 55 ppb) than during the autumn observation period (38 ± 13 ppb;
223 median: 39 ppb), suggesting a more oxidizing background in the spring observation period. In contrast, SO₂ and NO₂ showed
224 intermittent spikes in both observation periods, implying episodic impacts from transport and/or local emissions. Notably,
225 the CS remained similar across observation periods, with values of $(7.9 \pm 5.3) \times 10^{-3}$ s⁻¹ (median: 6.5×10^{-3} s⁻¹) in the
226 autumn observation period and $(8.1 \pm 3.8) \times 10^{-3}$ s⁻¹ (median: 7.2×10^{-3} s⁻¹) in the spring observation period,
227 indicating that the observation-period difference in NPF occurrence is unlikely driven solely by differences in the pre-
228 existing particle sink.

229 NPF events were frequently observed at the TU site and were associated with pronounced differences between the two
230 observation periods in PNSD and estimated CCN concentrations. In total, 43 NPF events, 6 Undefined days, and 9 Non-
231 Event days were identified during the 58 measurement days. The autumn observation period included 25 NPF days, 1
232 Undefined day, and 3 Non-Event days, whereas the spring observation period included 18 NPF days, 5 Undefined days, and
233 6 Non-Event days. Based on Fig. 3g, NPF occurrence displayed a marked observation-period contrast, with NPF observed
234 on 86.2 % of the measurement days during the autumn observation period but only on 62.1 % during the spring observation
235 period. Fig. 3e shows that the total particle number concentration (N_{3-700}) was substantially higher during the autumn
236 observation period, with an arithmetic mean $\pm$ standard deviation of $(10.5 \pm 9.8) \times 10^3$ cm⁻³ and a median of 7.1×10^3
237 cm⁻³, than during the spring observation period, when the corresponding values were $(5.3 \pm 6.8) \times 10^3$ and 2.9×10^3 cm
238 ⁻³, respectively. The median particle diameter (median D_p) was smaller during the autumn observation period, with an
239 arithmetic mean $\pm$ standard deviation of 37 ± 14 nm and an observation-period median of 39 nm, than during the spring
240 observation period, when the corresponding values were 45 ± 34 and 38 nm, respectively. This difference indicates a
241 stronger contribution from smaller particles during the autumn observation period. Figure 3f further presents the estimated
242 CCN concentrations and the fractional contributions from different modes. Estimated CCN concentrations were higher
243 during the autumn observation period, with an arithmetic mean $\pm$ standard deviation of $(2.8 \pm 1.7) \times 10^3$ cm⁻³ and a
244 median of 2.4×10^3 cm⁻³. These higher concentrations were accompanied by more frequent and persistent enhancements in
245 the nucleation- and Aitken-mode fractions and episodic reductions in the accumulation-mode fraction, suggesting a shift of

246 the particle population toward the small-to-intermediate size range. In contrast, the spring observation period showed a lower
 247 arithmetic mean $\pm$ standard deviation estimated CCN concentration of $(1.2 \pm 0.6) \times 10^3 \text{ cm}^{-3}$ and a median of $0.96 \times$
 248 10^3 cm^{-3} , together with weaker and less persistent increases in the nucleation- and Aitken-mode fractions and a more
 249 dominant background contribution from the accumulation mode. Together, these observations highlight strong observation-
 250 period differences of particle sources and CCN-relevant size structure at the TU site and provide context for the process-
 251 based analysis in the following sections.



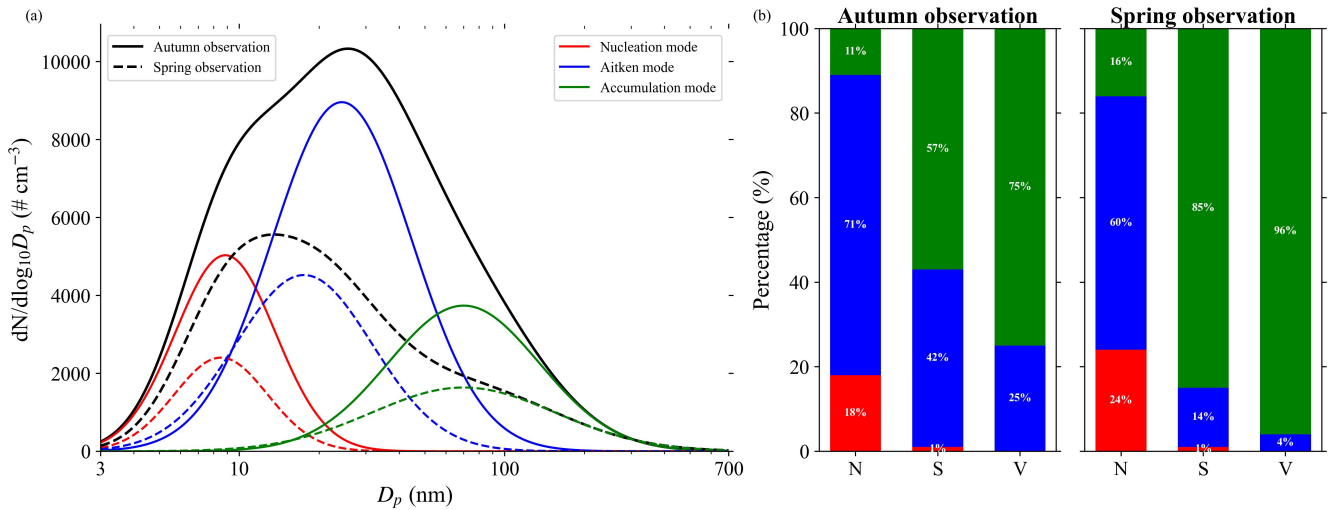
252

253 **Figure 3: Time series of (a) wind speed and wind direction, (b) ambient temperature and relative humidity, (c) O₃ concentration**
 254 **and NO₂ concentration, (d) SO₂ concentration and Condensation Sink, (e) median particle diameter and particle number**
 255 **concentration in the size range of 3–700 nm, (f) CCN concentration and percentage contributions of the nucleation mode, Aitken**
 256 **mode, and accumulation mode, (g) PNSD during the spring and autumn observation periods.**

257 **3.2 PNSD and number concentration responses**

258 **3.2.1 Mean PNSD and modal contributions**

259 The mean PNSD and modal contributions reveal clear differences in the campaign-mean particle size structure and surface-
260 area/volume partitioning between the autumn and spring observation periods. Figure 4a shows that the mean PNSD during
261 the two observation periods at the TU site was typically multimodal, reflecting the combined influences of secondary particle
262 production, particle growth, and the pre-existing aerosol population. The total particle number concentration differed
263 markedly between the two observation periods. The arithmetic mean $\pm$ standard deviation of N_{3-700} was $(10.5 \pm 9.8) \times 10^3$
264 cm^{-3} during the autumn observation period and $(5.3 \pm 6.8) \times 10^3 \text{ cm}^{-3}$ during the spring observation period, with the
265 former being approximately 2.0 times higher than the latter (Fig. 4a). In terms of modal partitioning, Fig. 4b indicates that
266 while the Aitken mode dominates number concentration in both periods, the surface area and volume are strongly controlled
267 by the accumulation mode in the spring observation period, accounting for 85 % (surface area) and 96 % (volume). In
268 contrast, during the autumn observation period the Aitken mode contributes substantially more to surface area (42 %) and
269 volume (25 %) than in the spring observation period (14 % and 4 %, respectively), consistent with a particle population
270 shifted toward smaller-to-intermediate sizes. These differences between the two observation periods provide a baseline for
271 interpreting event-day diurnal changes and their implications for CCN-relevant size fractions.

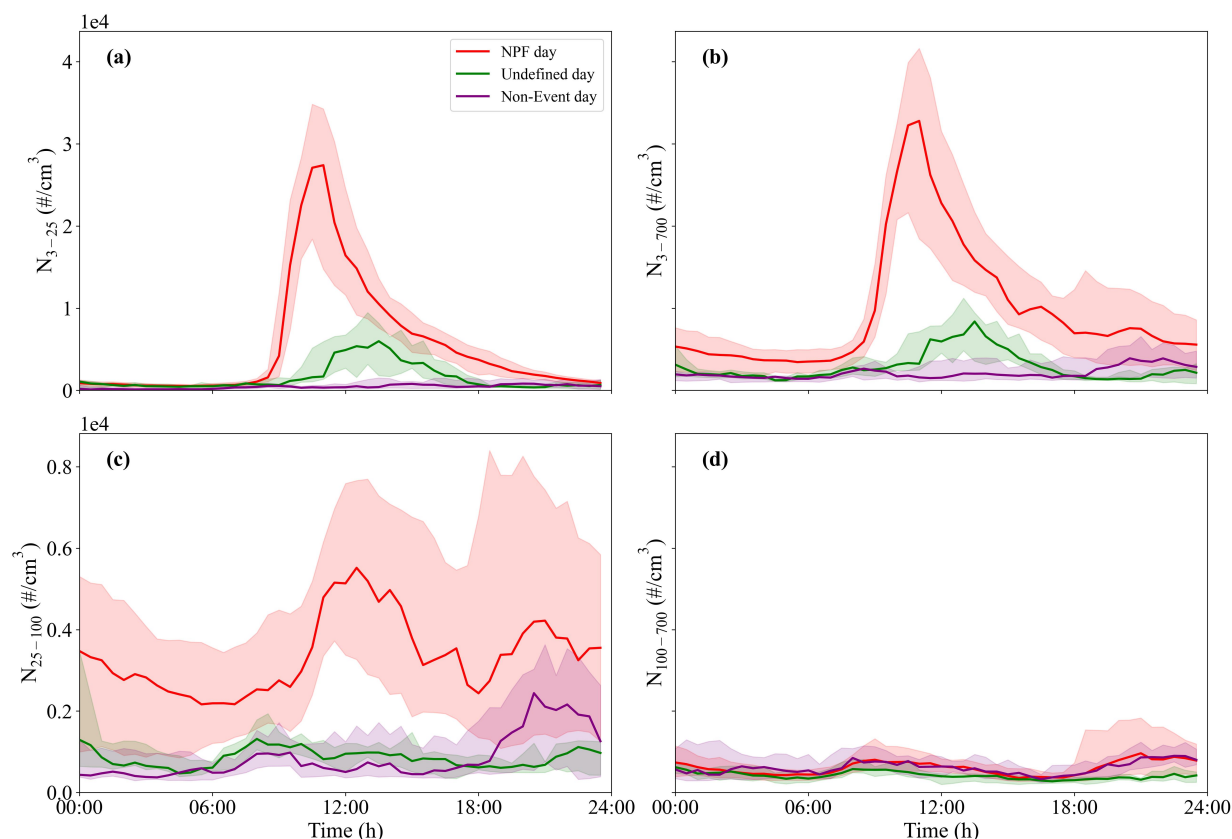


272
273 **Figure 4: (a) Particle number size distribution characteristics and (b) modal contributions to number (N), surface area (S), and**
274 **volume (V) distributions during the spring and autumn observation periods.**

275 **3.2.2 Diurnal variations of size-segregated number concentrations**

276 The diurnal profiles of size-segregated particle number concentrations differed clearly among NPF, Undefined, and Non-
277 Event days. Figure 5 summarizes diurnal profiles of particle number concentrations for the nucleation mode (N_{3-25}), Aitken

278 mode (N_{25-100}), accumulation mode ($N_{100-700}$), and total measured size range (N_{3-700}) across the three day categories. On NPF
 279 days, N_{3-25} increased rapidly during the morning, reached a pronounced maximum at approximately 11:00–12:00 local time,
 280 and subsequently declined (Fig. 5a). Undefined days exhibited a weaker and broader increase from late morning to afternoon,
 281 whereas Non-Event days maintained substantially lower N_{3-25} concentrations without a preceding N_{3-25} peak. N_{3-700} showed
 282 a similar pattern, with the highest and most pronounced daytime maximum occurring on NPF days (Fig. 5b). N_{25-100} on NPF
 283 days exhibited a broad daytime enhancement from approximately 11:00 to 15:00, followed by a secondary increase in the
 284 evening (Fig. 5c). The daytime enhancement is consistent with the growth of newly formed particles into the Aitken mode,
 285 whereas the evening increase may also be influenced by local urban emissions. Undefined days showed relatively weak
 286 variations in N_{25-100} , while Non-Event days exhibited a more evident evening increase without a preceding increase in the
 287 nucleation mode. Differences in $N_{100-700}$ among the three categories were relatively small, although modest morning and
 288 evening enhancements were observed (Fig. 5d). These diurnal statistics indicate that the impact of NPF on the size
 289 distribution depends not only on daytime particle production, but also on the persistence of growth into the Aitken mode.

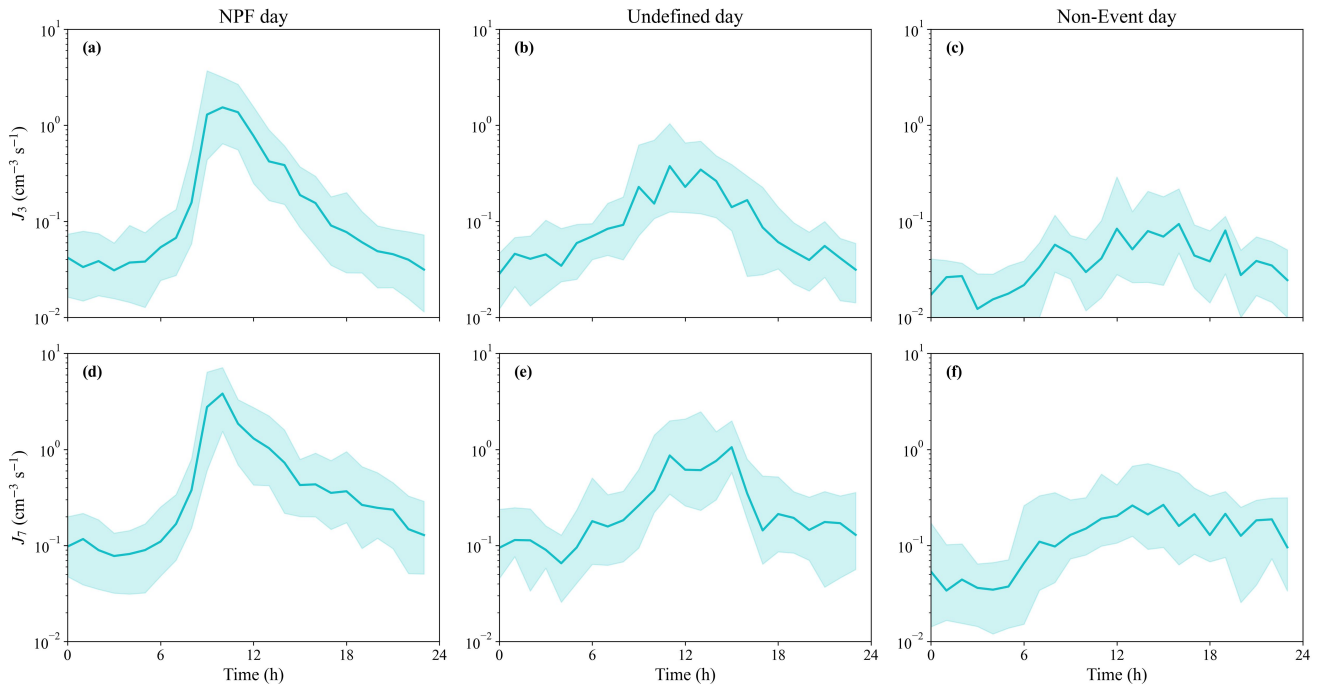


290
 291 **Figure 5: Diurnal variation of aerosol number concentrations ($\# \text{ cm}^{-3}$) at the size ranges of (a) 3–25 nm, (b) 3–700 nm, (c) 25–100**
 292 **nm, and (d) 100–700 nm, on NPF, Undefined, and Non-Event days. Shaded areas represent the interquartile range (25th to 75th**
 293 **percentiles).**

294 **3.3 Factors controlling the formation and development of NPF events**

295 **3.3.1 Formation and growth characteristics**

296 Figure 6 summarizes the diurnal variations in particle formation rates at 3 nm (J_3) and 7 nm (J_7) for the three day categories.
297 On NPF days, both formation rates increased rapidly during the morning and reached pronounced maxima at approximately
298 09:00–11:00, followed by a gradual decline. Undefined days exhibited weaker and less persistent daytime enhancements,
299 whereas Non-Event days generally showed the lowest formation-rate signals and lacked a distinct morning peak. These
300 contrasting diurnal patterns support the occurrence of active daytime particle formation on NPF days.
301 During 08:00–16:59, the mean J_3 and J_7 on NPF days were $1.2 \pm 2.0 \text{ cm}^{-3} \text{ s}^{-1}$ and $2.2 \pm 3.3 \text{ cm}^{-3} \text{ s}^{-1}$, respectively, with
302 corresponding median values of 0.44 and $1.12 \text{ cm}^{-3} \text{ s}^{-1}$. The observed J_3 was of the same order of magnitude as the
303 formation rates reported at Nam Co ($J_4=1.2 \pm 0.6 \text{ cm}^{-3} \text{ s}^{-1}$) (Tang et al., 2023) and the Mt. Yulong station ($J_3: 1.2 \text{ cm}^{-3} \text{ s}^{-1}$)
304 (Shang et al., 2018). The arithmetic mean $\pm$ standard deviation values of GR_{3-7} and GR_{7-20} were 3.7 ± 1.1 and 2.0 ± 1.7
305 nm h^{-1} , respectively, with corresponding median values of 3.6 and 1.3 nm h^{-1} . These growth rates were broadly comparable
306 to values at Nam Co ($\text{GR}_{4-25}: 4.0 \pm 1.2 \text{ nm h}^{-1}$) and Mt. Yulong (3.2 nm h^{-1}), but higher than the value reported at the NCO-P
307 station ($1.2 \pm 0.7 \text{ nm h}^{-1}$) (Venzac et al., 2008). In summary, the J and GR values at TU are well within the ranges reported
308 for global high-altitude environments, indicating that the site experiences characteristic high-altitude NPF with strong
309 daytime formation and sufficiently rapid growth to promote downstream enhancement of Aitken-mode number
310 concentrations.



311

312 **Figure 6: Diurnal variations of the formation rates J_3 during (a) NPF day, (b) Undefined day, and (c) Non-Event day periods. The**
 313 **corresponding diurnal variations of the formation rate J_7 are shown in panels (d), (e) and (f). The shaded areas represent the 25th**
 314 **and 75th percentile boundaries, and the solid lines denote the median values.**

315 3.3.2 Condensation sink and its role

316 CS represents the ability of the pre-existing aerosol population to remove condensable vapors via condensation, while CoagS
 317 describes the loss of freshly formed clusters and ultrafine particles through collision and coalescence with larger background
 318 particles (Victor et al., 2024). Figure 7 shows the diurnal variations of CS and CoagS for different day types and observation
 319 periods. Both sink terms exhibit clear diurnal structure and substantial variability, indicating that the removal capacity for
 320 vapors and nascent particles can change markedly over the course of a day and between different regimes.

321 Consistent with many studies reporting that NPF tends to be favored under relatively low CS (Cai et al., 2017; Saha et al.,
 322 2018; Kalivitis et al., 2019; Kalkavouras et al., 2020; Aktypis et al., 2023), the TU site nevertheless shows that NPF can
 323 occur even when CS is not minimal. The mean CS levels ($\pm 1\sigma$) were $(6.9 \pm 4.5) \times 10^{-3} \text{ s}^{-1}$ on NPF days, $(5.1 \pm 4.3) \times$
 324 10^{-3} s^{-1} on Undefined days, and $(6.4 \pm 4.4) \times 10^{-3} \text{ s}^{-1}$ on Non-Event days (Fig. 7a–c), with corresponding median values
 325 of 5.8×10^{-3} , 3.5×10^{-3} , and $5.0 \times 10^{-3} \text{ s}^{-1}$. Thus, CS on NPF days was slightly higher than that on Non-Event days, and
 326 the NPF-day mean CS at TU is higher than values reported for remote plateau background sites in China (Tang et al., 2023),
 327 yet lower than those reported for the major urban environment of Beijing (Du et al., 2017), suggesting an intermediate sink
 328 environment characteristic of a high-altitude urban setting. Moreover, the mean CS values were broadly similar between the
 329 autumn and spring observation periods, at $(6.9 \pm 4.1) \times 10^{-3}$ and $(6.2 \pm 4.7) \times 10^{-3} \text{ s}^{-1}$, respectively, with corresponding
 330 median values of 5.9×10^{-3} and $4.5 \times 10^{-3} \text{ s}^{-1}$ (Fig. 7d–e). Therefore, differences in the pre-existing particle sink were
 331 unlikely to be the primary explanation for the contrast in NPF frequency between the two observation periods.

332 In contrast, CoagS shows a stronger separation among day types and observation periods. The mean CoagS values were $(4.3$
 333 $\pm 2.6) \times 10^{-5} \text{ s}^{-1}$ on NPF days, $(2.2 \pm 1.2) \times 10^{-5} \text{ s}^{-1}$ on Undefined days, and $(2.5 \pm 1.4) \times 10^{-5} \text{ s}^{-1}$ on Non-Event days,
 334 with corresponding median values of 3.6×10^{-5} , 1.9×10^{-5} , and $2.2 \times 10^{-5} \text{ s}^{-1}$, respectively (Fig. 7f–h). The mean CoagS
 335 was also higher during the autumn observation period $(4.5 \pm 2.6) \times 10^{-5} \text{ s}^{-1}$ than during the spring observation period $(2.9$
 336 $\pm 2.0) \times 10^{-5} \text{ s}^{-1}$, with corresponding median values of 3.9×10^{-5} and $2.4 \times 10^{-5} \text{ s}^{-1}$, respectively (Fig. 7i–j). Because
 337 CoagS reflects the scavenging loss of newly formed clusters and ultrafine particles, its elevated value during the autumn
 338 observation period indicates a stronger constraint on particle survival. However, NPF occurred more frequently during this
 339 period, suggesting that particle-production processes were sufficiently strong to offset the enhanced coagulation loss.

340 Taken together, these results suggest that the occurrence and development of NPF at TU are better interpreted as the
 341 outcome of competition between particle-production and loss processes rather than as being controlled by the sink alone.
 342 This interpretation is consistent with previous observations that NPF can be observed under moderate sinks when vapor
 343 production is sufficiently strong (Zhang et al., 2021; Sellegri et al., 2019; Wang et al., 2022; Baalbaki et al., 2021). In this
 344 framework, CoagS provides an additional constraint on whether newly formed clusters can survive long enough to grow into

larger sizes, while CS limits the availability of low-volatility vapors required for sustained growth; hence, event intensity and downstream impacts are expected to depend on the joint evolution of formation/growth rates and sinks over the diurnal cycle.

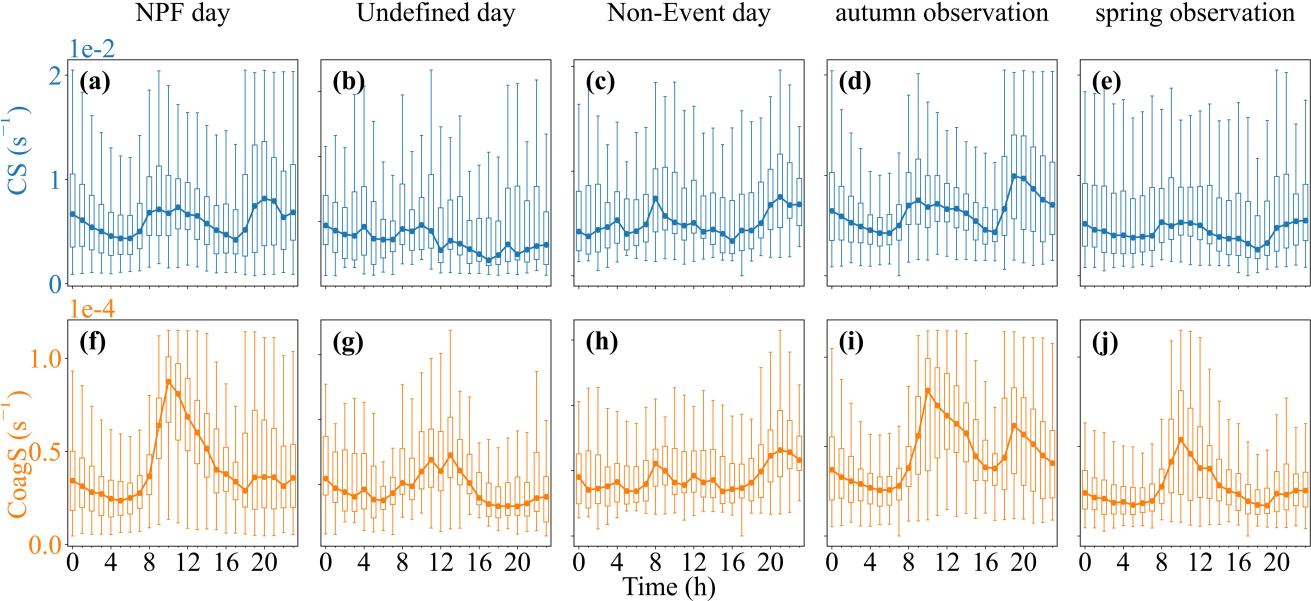


Figure 7: Diurnal variations of condensation sink and coagulation sink for different event classifications and observation periods.

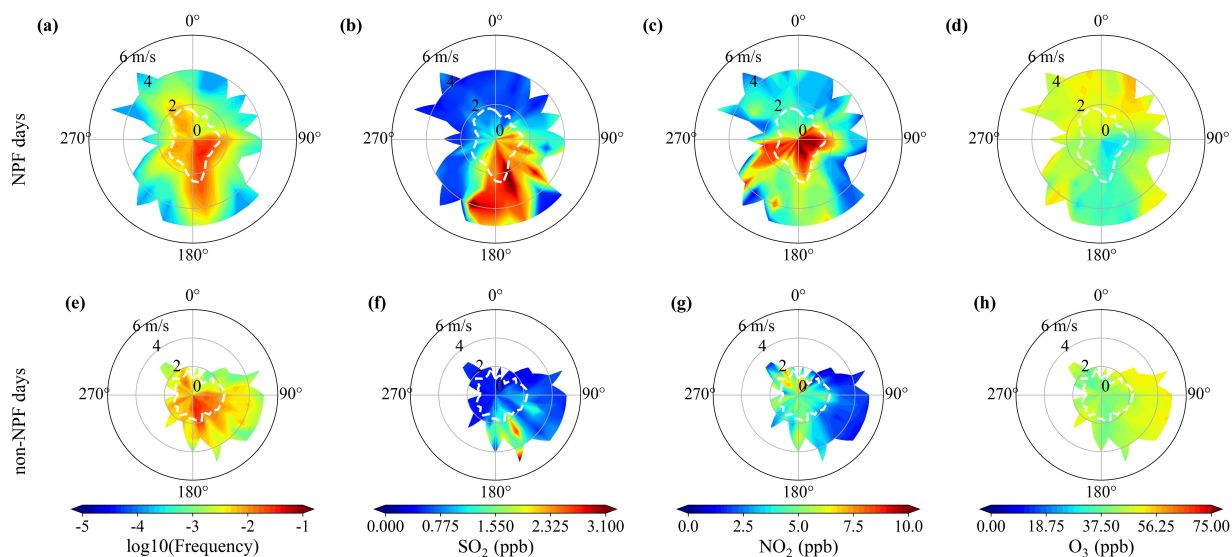
3.3.3 Meteorology and precursor modulation, with transport context

Meteorological conditions during the study period exhibited clear diurnal variability, consistent with the dependence of NPF on atmospheric state and precursor availability reported in previous studies (Hakala et al., 2022; Kalkavouras et al., 2020; Kalkavouras et al., 2019; Victor et al., 2024; Singh et al., 2025). The site was predominantly under clear to partly cloudy conditions with sufficient solar radiation, occasionally interrupted by precipitation. Notably, an extended rainfall episode occurred from 5 to 6 November during the autumn observation period, during which no NPF events were identified. The absence of NPF during this episode may have been associated with wet scavenging and reduced photochemical production of condensable vapors under rainy and cloudy conditions.

To examine the associations of meteorological conditions and key gaseous precursors with NPF, we compared SO₂, O₃, and NO₂, together with temperature, RH, and wind speed, across day types and between the two observation periods. As described in Sect. 3.1, the spring observation period was warmer and slightly windier, whereas the autumn observation period was more humid. The comparatively weaker ventilation during the autumn observation period may have favored the episodic accumulation of gaseous precursors and particles.

During the autumn observation period, SO₂ and NO₂ mixing ratios were higher on NPF days than on non-NPF days. The mean SO₂ mixing ratio was 1.9 ± 2.0 ppb on NPF days and 0.7 ± 0.7 ppb on non-NPF days, with corresponding median values of 0.9 and 0.5 ppb, respectively. The mean NO₂ mixing ratios were 7.2 ± 4.9 and 4.6 ± 3.9 ppb, with corresponding

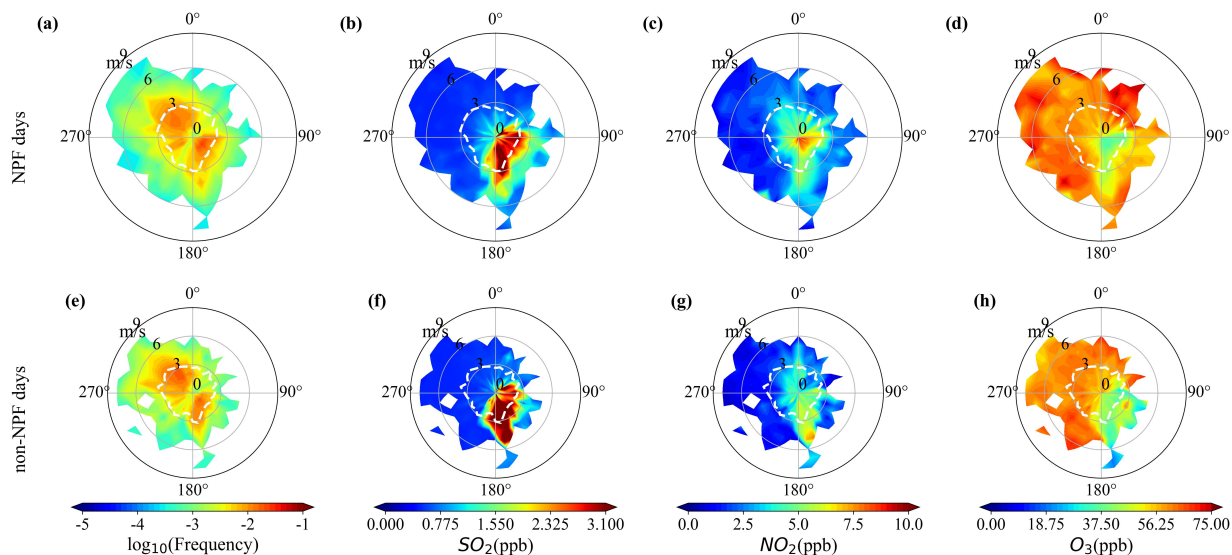
365 median values of 5.9 and 3.2 ppb, respectively. Wind-sector analysis further showed that elevated SO_2 and NO_2 mixing
 366 ratios occurred more frequently under southerly winds on NPF days, whereas generally lower values were observed in the
 367 corresponding sectors on non-NPF days (Fig. 8). Because SO_2 oxidation by $\text{OH}\cdot$ produces H_2SO_4 , and H_2SO_4 is widely
 368 recognized as a key nucleation precursor and critical for early particle growth, the higher SO_2 concentrations observed on
 369 NPF days suggest that sulfur-containing precursors may have played an important role in NPF during the autumn
 370 observation period (Olin et al., 2020; Yao et al., 2018; Kerminen et al., 2018). Although elevated NO_2 can alter atmospheric
 371 radical chemistry and potentially reduce OH availability under some conditions, the clearly elevated SO_2 observed on NPF
 372 days suggests that plentiful SO_2 increases the potential for H_2SO_4 formation. This interpretation is further supported by Fig.
 373 S4, which shows that during the particle-formation period SO_2 concentrations on NPF days are clearly higher than those on
 374 non-NPF days. Moreover, for periods with available spectral measurements, the relative H_2SO_4 -related proxy was also
 375 higher on NPF days during the particle-formation period (Fig. S5), providing additional evidence for an association between
 376 photochemical H_2SO_4 production and autumn NPF. These results suggest that the increased availability of sulfur-containing
 377 precursors may have partly compensated for potentially unfavorable effects associated with elevated NO_x and supported
 378 NPF occurrence (Gao et al., 2025). Although the proxy is not a direct measurement of H_2SO_4 , these results support an
 379 important contribution from sulfur-containing precursors to autumn NPF rather than demonstrating their exclusive control.



380
 381 **Figure 8: Wind-sector analysis comparing the distributions of (a) wind speed and wind direction frequency together with sector-**
 382 **averaged concentrations of (b) SO_2 , (c) NO_2 , and (d) O_3 , for NPF days during the autumn observation period; panels (e), (f),**
 383 **and (h) show the corresponding wind-sector frequency and gas concentrations for non-NPF days during the autumn observation**
 384 **period.**

385 During the spring observation period, no single, well-defined factor controlling NPF occurrence was evident. As shown in
 386 Figs. 9 and S6, SO_2 , NO_2 , and O_3 exhibited differences between NPF and non-NPF days during certain hours and under

387 specific wind conditions. However, no consistent separation between the two categories was observed across all gaseous
 388 species or throughout the particle-formation period. Wind speed and wind direction likewise did not show a distinctive
 389 pattern that consistently characterized NPF days. These results suggest that spring NPF was more likely associated with the
 390 combined effects of multiple processes, including precursor availability, atmospheric oxidation, and boundary-layer
 391 evolution, rather than with any single dominant factor (Wu et al., 2024). Given the relatively weak and inconsistent contrasts
 392 in the measured inorganic gaseous precursors, a contribution from VOC-related oxidation processes cannot be excluded,
 393 particularly for the subsequent growth of newly formed particles (Zhang et al., 2026; Yang et al., 2026). However, because
 394 direct observations of VOCs and their oxidation products are not available in this study, their specific role cannot be further
 395 constrained and still requires additional investigation.
 396 Overall, the comparison between the two observation periods indicates differences in the factors associated with NPF,
 397 although the relatively short measurement periods preclude establishing a general seasonal pattern. During the autumn
 398 observation period, NPF was associated with higher SO_2 concentrations and an enhanced relative H_2SO_4 -related proxy
 399 during the particle-formation period, suggesting an important contribution from sulfur-containing precursors rather than
 400 demonstrating a uniquely sulfur-precursor-driven regime. Elevated NO_2 may have modified atmospheric radical chemistry,
 401 but its net effect on NPF could not be determined from the available measurements. In contrast, during the spring
 402 observation period, no single dominant factor was identified. Instead, precursor availability, atmospheric oxidation,
 403 boundary-layer evolution, and potentially VOC-related oxidation may have jointly affected particle formation and growth.
 404 Because H_2SO_4 , ammonia, amines, VOCs, and their oxidation products were not directly measured, their respective
 405 contributions could not be quantified, and the detailed molecular mechanisms during both observation periods remain
 406 uncertain.



408 **Figure 9: Wind-sector analysis comparing the distributions of (a) wind speed and wind direction frequency together with sector-**
409 **averaged concentrations of (b) SO₂, (c) NO₂, and (d) O₃, for NPF days during the spring observation period; panels (e), (f), (g), and**
410 **(h) show the corresponding wind-sector frequency and gas concentrations for non-NPF days during the spring observation period.**

411 **3.4 Modulation of CCN by NPF in urban air**

412 To quantify the influence of NPF on CCN in the urban atmosphere of the Tibetan Plateau, we examined both the diurnal
413 evolution and the distribution of estimated CCN for different event categories as well as for the two periods (spring and
414 autumn). Because direct measurements of CCN concentration were unavailable in this study, CCN was estimated from the
415 measured PNSD using the κ -Köhler framework described in Sect. 2.3, assuming a constant particle hygroscopicity parameter
416 κ of 0.12 and a supersaturation S of 1.2 %. Because the estimated CCN concentrations depend on these assumptions, a
417 sensitivity analysis was conducted using κ values of 0.08, 0.12, and 0.20 and supersaturations of 0.6 %, 0.8 %, and 1.2 %
418 (Fig. S7). Although the absolute CCN concentrations varied with κ and S , estimated CCN remained consistently higher
419 during the autumn observation period than during the spring observation period across the tested parameter
420 combinations. The estimated CCN concentrations were higher than $N_{100-700}$, because the assumed κ and supersaturation
421 corresponded to a critical activation diameter below 100 nm, allowing part of the Aitken-mode particle population to
422 contribute to the estimated CCN.

423 Figure 10a shows clear differences in the diurnal variation of estimated CCN concentrations among NPF, Undefined, and
424 Non-Event days. NPF days generally exhibited the highest CCN concentrations, with pronounced daytime variations and a
425 marked enhancement during the late afternoon and evening. This late-day enhancement is consistent with the continued
426 growth and survival of newly formed particles into CCN-relevant sizes (Shen et al., 2019). Undefined days showed the
427 lowest CCN concentrations and relatively weak diurnal variability. Non-Event days generally exhibited intermediate CCN
428 concentrations, including an evening increase that may reflect the influence of pre-existing particles and local urban
429 emissions rather than daytime NPF. The distributions in Fig. 10b likewise show that estimated CCN concentrations were
430 generally higher and more broadly distributed on NPF days than on Undefined and Non-Event days. To further examine the
431 role of particle growth, NPF days were divided into high- and low- N_{25-100} groups using the observation-period-specific
432 median of daily mean N_{25-100} during 09:00–18:00. The high- N_{25-100} group exhibited higher estimated CCN concentrations,
433 particularly in the afternoon and evening (Fig. S8), supporting the importance of continued particle growth and survival for
434 potential CCN production.

435 The distributions in Fig. 10b show substantially higher estimated CCN concentrations during the autumn observation period
436 than during the spring observation period. The median (interquartile range) estimated CCN concentration was $2.4 \times 10^3 \text{ cm}^{-3}$
437 ($1.5\text{--}3.8 \times 10^3 \text{ cm}^{-3}$) during the autumn observation period, with an arithmetic mean $\pm$ standard deviation of $(2.8 \pm 1.7) \times 10^3$
438 cm^{-3} . During the spring observation period, the corresponding median was $0.96 \times 10^3 \text{ cm}^{-3}$ ($0.70\text{--}1.5 \times 10^3 \text{ cm}^{-3}$), and the
439 arithmetic mean $\pm$ standard deviation was $(1.2 \pm 0.6) \times 10^3 \text{ cm}^{-3}$. These differences coincided with the higher NPF frequency
440 during the autumn observation period and suggest that frequent NPF, together with subsequent particle growth, may have
441 contributed to the higher estimated CCN-relevant particle concentrations at the TU site.

Overall, our results indicate that NPF days were associated with higher estimated CCN concentrations in the TP urban atmosphere, although the magnitude of the estimates depended on the assumed κ and supersaturation. The pronounced late-day enhancement on NPF days, particularly in the high- N_{25-100} group, highlights the importance of sustained post-formation growth and particle survival in determining the potential CCN response. At the observation-period scale, the higher estimated CCN concentrations during the autumn observation period may reflect the combined influence of frequent NPF and favorable particle-growth conditions. Because CCN concentrations were estimated rather than directly measured, these results indicate potential CCN production rather than direct confirmation of CCN activation.

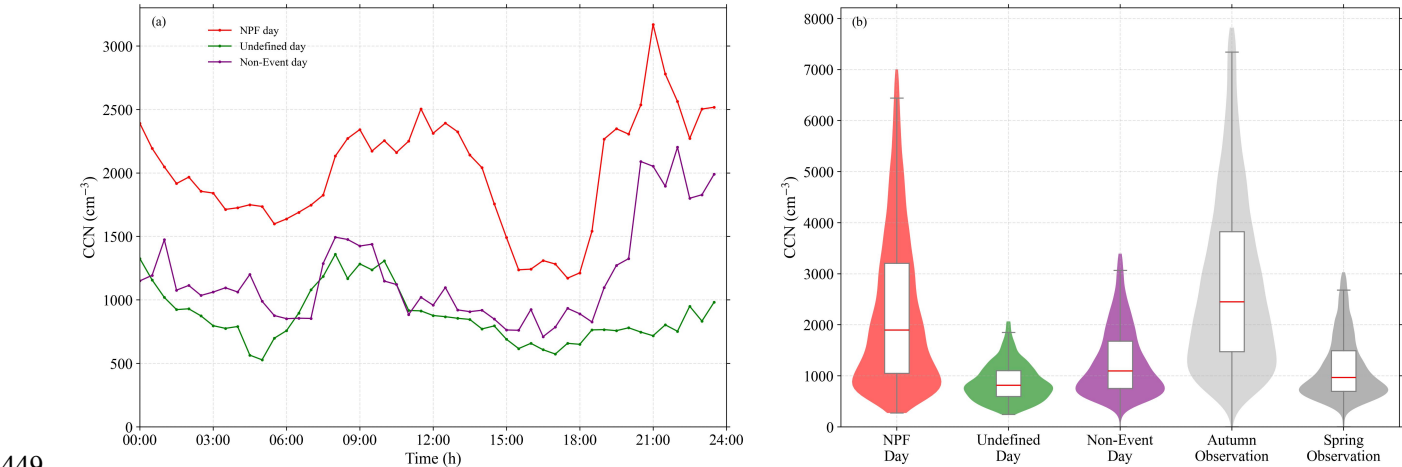


Figure 10: (a) Diurnal variations and (b) statistical distributions of estimated CCN concentrations for NPF, Undefined, and Non-Event days and for the autumn and spring observation periods. CCN concentrations were estimated using $\kappa = 0.12$ and $S = 1.2\%$.

4 Conclusion

This study provides a comprehensive characterization of NPF in Lhasa, a high-altitude urban center on the Tibetan Plateau, with particular emphasis on the controlling factors of NPF and its implications for CCN during the spring and autumn observation periods. Frequent NPF was observed throughout the campaigns. The contrast between the two observation periods in NPF occurrence was pronounced, with event frequencies of 86.2 % during the autumn observation period and 62.1 % during the spring observation period, indicating that the NPF regime in Lhasa is highly sensitive to variations in meteorology and atmospheric chemistry between the observation periods.

The results indicate that differences in the pre-existing particle sink alone cannot explain the contrast in NPF frequency between the two observation periods, and that precursor availability and atmospheric oxidation likely also played important roles. The CS remained comparable between the two observation periods, suggesting that the observed contrast in NPF frequency cannot be explained by sink suppression alone. Instead, the chemical–meteorological context differs substantially across observation periods. During the autumn observation period, NPF days were associated with elevated SO₂ and a higher relative H₂SO₄-related proxy during the particle-formation period, suggesting that sulfur-containing precursors likely

465 contributed to particle formation and early growth. In contrast, the spring observation period NPF did not show a single,
466 well-defined controlling factor, but was more likely influenced by the combined effects of precursor supply, atmospheric
467 oxidation, and boundary-layer evolution. Under such conditions, VOC-related oxidation may contribute to the early growth
468 of newly formed particles, although its specific role remains to be further constrained.

469 A key outcome of this work is that NPF days were associated with higher estimated CCN concentrations in Lhasa, and that
470 the potential CCN response depended critically on whether newly formed particles continued to grow and survive after
471 formation. Estimated CCN concentrations were generally higher on NPF days than on Undefined and Non-Event days.
472 Moreover, NPF days with higher N_{25-100} exhibited greater afternoon and evening CCN enhancements than those with lower
473 N_{25-100} , supporting the importance of continued particle growth and survival in determining whether newly formed particles
474 reach CCN-relevant sizes. The mean estimated CCN concentration during the autumn observation period was more than
475 twice that during the spring observation period, suggesting that frequent NPF together with favorable particle-growth
476 conditions may have contributed to higher CCN-relevant particle concentrations during the autumn measurements. These
477 findings improve our understanding of the potential contribution of urban NPF to CCN-relevant particle populations in high-
478 altitude environments over the Tibetan Plateau.

479 Despite the insights gained in this study, several limitations should be acknowledged. First, the day classification was based
480 primarily on the daily PNSD evolution and modal development, supported by particle number concentrations in the 3-25 and
481 25-100 nm ranges and particle growth rates. Although these supporting metrics reduced reliance on visual inspection alone,
482 some classification uncertainty remained for days with weak, discontinuous, or ambiguous particle evolution; these days
483 were therefore retained as Undefined days and included in the non-NPF group for comparisons between NPF and non-NPF
484 conditions. Second, CCN concentrations were not directly measured but estimated from the measured PNSD using the κ -
485 Köhler framework, which may introduce uncertainties associated with the assumed hygroscopicity parameter and
486 supersaturation. Therefore, the estimated CCN values are more suitable for interpreting relative differences and response
487 patterns than for over-interpreting their absolute magnitudes. In addition, due to the lack of direct observations of VOCs and
488 their oxidation products, the mechanisms of NPF, especially during the spring observation period, could not be further
489 constrained. Future studies should combine longer-term continuous observations with direct CCN measurements and
490 additional observations of VOCs, H_2SO_4 , and related oxidation products, in order to better identify the controlling factors of
491 NPF and its contribution to CCN in high-altitude urban environments over the Tibetan Plateau.

492 **Code and data availability**

493 The elevation data used in this study are openly available from the Geospatial Data Cloud at <https://www.gscloud.cn>.
494 The raw observational datasets used in this study have been deposited in Zenodo and can be freely downloaded from
495 <https://doi.org/10.5281/zenodo.19876491>.

496 The codes used for data processing and figure generation have been deposited in a separate Zenodo repository and can be
497 freely downloaded from <https://doi.org/10.5281/zenodo.19879177>.

498 **Author contributions**

499 QM and LW wrote the manuscript. QM, LW, GZ, CY, JS and TZ discussed the original idea and results. JS, FS, TL, YG,
500 and YC conducted the field measurement. QM, LW and JS processed and analysed the data.

501 **Competing interests**

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

503 **Financial support**

504 This study was financially supported by the National Natural Science Foundation of China (42405083), the Open Project
505 of the Key Laboratory of Biodiversity and Environment on the Qinghai-Tibet Plateau, Ministry of Education
506 (KLBE2025010), the Tibetan Key Research and Development Program Project (XZ202403ZY0022).

507 **References**

- 508 Aktypis, A., Kaltsonoudis, C., Skyllakou, K., Matrali, A., Vasilakopoulou, C. N., Florou, K., and Pandis, S. N.: Infrequent
509 new particle formation in a coastal Mediterranean city during the summer, *Atmospheric Environment*, 302, 119732,
510 <https://doi.org/10.1016/j.atmosenv.2023.119732>, 2023.
- 511 Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.-K., and Rogelj, J.:
512 Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the
513 Intergovernmental Panel on Climate Change; technical summary, 2021.
- 514 Baalbaki, R., Pikridas, M., Jokinen, T., Laurila, T., Dada, L., Bezantakos, S., Ahonen, L., Neitola, K., Maisser, A.,
515 Bimenyimana, E., Christodoulou, A., Unga, F., Savvides, C., Lehtipalo, K., Kangasluoma, J., Biskos, G., Petäjä, T.,
516 Kerminen, V. M., Sciare, J., and Kulmala, M.: Towards understanding the characteristics of new particle formation in the
517 Eastern Mediterranean, *Atmos. Chem. Phys.*, 21, 9223–9251, 10.5194/acp-21-9223-2021, 2021.
- 518 Bianchi, F., Junninen, H., Bigi, A., Sinclair, V. A., Dada, L., Hoyle, C. R., Zha, Q., Yao, L., Ahonen, L. R., Bonasoni, P.,
519 Buenrostro Mazon, S., Hutterli, M., Laj, P., Lehtipalo, K., Kangasluoma, J., Kerminen, V. M., Kontkanen, J., Marinoni, A.,
520 Mirme, S., Molteni, U., Petäjä, T., Riva, M., Rose, C., Sellegri, K., Yan, C., Worsnop, D. R., Kulmala, M., Baltensperger, U.,
521 and Dommen, J.: Biogenic particles formed in the Himalaya as an important source of free tropospheric aerosols, *Nature*
522 *Geoscience*, 14, 4–9, 10.1038/s41561-020-00661-5, 2021.
- 523 Cai, R., Yang, D., Fu, Y., Wang, X., Li, X., Ma, Y., Hao, J., Zheng, J., and Jiang, J.: Aerosol surface area concentration: a
524 governing factor in new particle formation in Beijing, *Atmos. Chem. Phys.*, 17, 12327–12340, 10.5194/acp-17-12327-2017,
525 2017.
- 526 Casans, A., Casquero-Vera, J. A., Rejano, F., Lyamani, H., Cazorla, A., Zabala, I., Huang, W., Agro, M., Barreto, A.,
527 Rodriguez, S., Gonzalez, Y., Bianchi, F., Petaja, T., Olmo, F. J., Alados-Arboledas, L., Carinanos, P., Gysel-Beer, M., and
528 Titos, G.: Determining the impact of new particle formation events on cloud condensation nuclei (CCN) concentrations, *Sci*
529 *Total Environ*, 972, 179094, 10.1016/j.scitotenv.2025.179094, 2025.

530 Cramer, K. L., Guenther, A. B., and Smith, J. N.: Ultrafine aerosol formation and growth in a Southern California desert,
 531 *Aerosol Science and Technology*, 1–13, 10.1080/02786826.2026.2619538, 2026.
 532 Dal Maso, M., Kulmala, M., Riipinen, I., Wagner, R., Hussein, T., Aalto, P. P., and Lehtinen, K. E.: Formation and growth of
 533 fresh atmospheric aerosols: eight years of aerosol size distribution data from SMEAR II, Hyytiälä, Finland, *Boreal*
 534 *environment research*, 10, 323, 2005.
 535 Dinoi, A., Weinhold, K., Wiedensohler, A., and Contini, D.: Study of new particle formation events in southern Italy,
 536 *Atmospheric Environment*, 244, 117920, <https://doi.org/10.1016/j.atmosenv.2020.117920>, 2021.
 537 Du, W., Zhao, J., Wang, Y., Zhang, Y., Wang, Q., Xu, W., Chen, C., Han, T., Zhang, F., Li, Z., Fu, P., Li, J., Wang, Z., and
 538 Sun, Y.: Simultaneous measurements of particle number size distributions at ground level and 260 m on a meteorological
 539 tower in urban Beijing, China, *Atmos. Chem. Phys.*, 17, 6797–6811, 10.5194/acp-17-6797-2017, 2017.
 540 Gao, Z., Wang, F., Du, W., Wang, S., Sun, Y., Yang, W., Wang, X., Han, B., and Bai, Z.: Elucidating particle number
 541 concentrations and unveiling source mechanisms at a prominent national background site on the northeastern Qinghai-
 542 Tibetan Plateau, *Sci Total Environ*, 969, 178928, 10.1016/j.scitotenv.2025.178928, 2025.
 543 Hakala, S., Vakkari, V., Bianchi, F., Dada, L., Deng, C., Dällenbach, K., Fu, Y., Jiang, J., Kangasluoma, J., and Kujansuu, J.:
 544 Observed coupling between air mass history, secondary growth of nucleation mode particles and aerosol pollution levels in
 545 Beijing, *Environmental science: atmospheres*, 2, 146–164, 2022.
 546 Hong, J., Tang, M., Wang, Q., Ma, N., Zhu, S., Zhang, S., Pan, X., Xie, L., Li, G., and Kuhn, U.: Measurement Report:
 547 Wintertime new particle formation in the rural area of the North China Plain—influencing factors and possible formation
 548 mechanism, *Atmospheric Chemistry and Physics*, 23, 5699–5713, 2023.
 549 Hu, Y., Yu, H., Kang, S., Yang, J., Rai, M., Yin, X., Chen, X., and Chen, P.: Aerosol–meteorology feedback diminishes the
 550 transboundary transport of black carbon into the Tibetan Plateau, *Atmospheric Chemistry and Physics*, 24, 85–107, 2024.
 551 Hussein, T., Atashi, N., Sogacheva, L., Hakala, S., Dada, L., Petäjä, T., and Kulmala, M.: Characterization of Urban New
 552 Particle Formation in Amman—Jordan, 10.3390/atmos11010079, 2020.
 553 Kalivitis, N., Kerminen, V. M., Kouvarakis, G., Stavroulas, I., Tzitzikalaki, E., Kalkavouras, P., Daskalakis, N.,
 554 Myriokefalitakis, S., Bougiatioti, A., Manninen, H. E., Roldin, P., Petäjä, T., Boy, M., Kulmala, M., Kanakidou, M., and
 555 Mihalopoulos, N.: Formation and growth of atmospheric nanoparticles in the eastern Mediterranean: results from long-term
 556 measurements and process simulations, *Atmos. Chem. Phys.*, 19, 2671–2686, 10.5194/acp-19-2671-2019, 2019.
 557 Kalkavouras, P., Bougiatioti, A., Hussein, T., Kalivitis, N., Stavroulas, I., Michalopoulos, P., and Mihalopoulos, N.:
 558 Regional New Particle Formation over the Eastern Mediterranean and Middle East, 10.3390/atmos12010013, 2021.
 559 Kalkavouras, P., Bougiatioti, A., Kalivitis, N., Stavroulas, I., Tombrou, M., Nenes, A., and Mihalopoulos, N.: Regional new
 560 particle formation as modulators of cloud condensation nuclei and cloud droplet number in the eastern Mediterranean,
 561 *Atmos. Chem. Phys.*, 19, 6185–6203, 10.5194/acp-19-6185-2019, 2019.
 562 Kalkavouras, P., Bougiatioti, A., Grivas, G., Stavroulas, I., Kalivitis, N., Liakakou, E., Gerasopoulos, E., Pilinis, C., and
 563 Mihalopoulos, N.: On the regional aspects of new particle formation in the Eastern Mediterranean: A comparative study
 564 between a background and an urban site based on long term observations, *Atmospheric Research*, 239, 104911,
 565 <https://doi.org/10.1016/j.atmosres.2020.104911>, 2020.
 566 Kerminen, V.-M., Chen, X., Vakkari, V., Petäjä, T., Kulmala, M., and Bianchi, F.: Atmospheric new particle formation and
 567 growth: review of field observations, *Environmental Research Letters*, 13, 103003, 10.1088/1748-9326/aadf3c, 2018.
 568 Kulmala, M., Maso, M. D., Mäkelä, J., Pirjola, L., Väkevä, M., Aalto, P., Mikkulainen, P., Hämeri, K., and O'dowd, C.: On
 569 the formation, growth and composition of nucleation mode particles, *Tellus B*, 53, 479–490, 2001.
 570 Kulmala, M., Petäjä, T., Nieminen, T., Sipilä, M., Manninen, H. E., Lehtipalo, K., Dal Maso, M., Aalto, P. P., Junninen, H.,
 571 Paasonen, P., Riipinen, I., Lehtinen, K. E. J., Laaksonen, A., and Kerminen, V.-M.: Measurement of the nucleation of
 572 atmospheric aerosol particles, *Nature Protocols*, 7, 1651–1667, 10.1038/nprot.2012.091, 2012.
 573 Lai, S., Qi, X., Huang, X., Lou, S., Chi, X., Chen, L., Liu, C., Liu, Y., Yan, C., Li, M., Liu, T., Nie, W., Kerminen, V. M.,
 574 Petäjä, T., Kulmala, M., and Ding, A.: New particle formation induced by anthropogenic–biogenic interactions on the
 575 southeastern Tibetan Plateau, *Atmos. Chem. Phys.*, 24, 2535–2553, 10.5194/acp-24-2535-2024, 2024.
 576 Lampilahti, A., Garmash, O., Aliaga, D., Arshinov, M., Davydov, D., Belan, B., Lampilahti, J., Kerminen, V.-M., Petäjä, T.,
 577 Kulmala, M., and Ezhova, E.: Insights into new particle formation in a Siberian boreal forest from nanoparticle ranking
 578 analysis, *Aerosol Research*, 3, 441–459, 10.5194/ar-3-441-2025, 2025.

Li, K., An, Y., Xu, J., Zhong, M., Zhao, W., and Qin, X.: Measurement report: Year-long chemical composition, optical properties, and sources of atmospheric aerosols in the northeastern Tibetan Plateau, *Atmospheric Chemistry and Physics*, 25, 12433–12450, 2025.

Liu, Y., Nie, W., Qi, X., Li, Y., Xu, T., Liu, C., Ge, D., Chen, L., Niu, G., Wang, J., Yang, L., Wang, L., Zhu, C., Wang, J., Zhang, Y., Liu, T., Zha, Q., Yan, C., Ye, C., Zhang, G., Hu, R., Huang, R.-J., Chi, X., Zhu, T., and Ding, A.: The Pivotal Role of Heavy Terpenes and Anthropogenic Interactions in New Particle Formation on the Southeastern Qinghai-Tibet Plateau, *Environmental Science & Technology*, 58, 19748–19761, 10.1021/acs.est.4c04112, 2024.

Olin, M., Kuuluvainen, H., Aurela, M., Kalliokoski, J., Kuittinen, N., Isotalo, M., Timonen, H. J., Niemi, J. V., Rönkkö, T., and Dal Maso, M.: Traffic-originated nanocluster emission exceeds H₂SO₄-driven photochemical new particle formation in an urban area, *Atmospheric Chemistry and Physics*, 20, 1–13, 2020.

Petters, M. D. and Kreidenweis, S. M.: A single parameter representation of hygroscopic growth and cloud condensation nucleus activity, *Atmos. Chem. Phys.*, 7, 1961–1971, 10.5194/acp-7-1961-2007, 2007.

Rose, C., Sellegri, K., Moreno, I., Velarde, F., Ramonet, M., Weinhold, K., Krejci, R., Andrade, M., Wiedensohler, A., Ginot, P., and Laj, P.: CCN production by new particle formation in the free troposphere, *Atmos. Chem. Phys.*, 17, 1529–1541, 10.5194/acp-17-1529-2017, 2017.

Saha, P. K., Robinson, E. S., Shah, R. U., Zimmerman, N., Apte, J. S., Robinson, A. L., and Presto, A. A.: Reduced Ultrafine Particle Concentration in Urban Air: Changes in Nucleation and Anthropogenic Emissions, *Environmental Science & Technology*, 52, 6798–6806, 10.1021/acs.est.8b00910, 2018.

Sellegri, K., Rose, C., Marinoni, A., Lupi, A., Wiedensohler, A., Andrade, M., Bonasoni, P., and Laj, P.: New Particle Formation: A Review of Ground-Based Observations at Mountain Research Stations, 10.3390/atmos10090493, 2019.

Shang, D., Hu, M., Zheng, J., Qin, Y., Du, Z., Li, M., Fang, J., Peng, J., Wu, Y., and Lu, S.: Particle number size distribution and new particle formation under the influence of biomass burning at a high altitude background site at Mt. Yulong (3410 m), China, *Atmospheric Chemistry and Physics*, 18, 15687–15703, 2018.

Shang, D., Tang, L., Fang, X., Wang, L., Yang, S., Wu, Z., Chen, S., Li, X., Zeng, L., Guo, S., and Hu, M.: Variations in source contributions of particle number concentration under long-term emission control in winter of urban Beijing, *Environmental Pollution*, 304, 119072, <https://doi.org/10.1016/j.envpol.2022.119072>, 2022.

Shen, L., Wang, H., Yin, Y., Chen, J., and Chen, K.: Observation of atmospheric new particle growth events at the summit of mountain Tai (1534 m) in Central East China, *Atmospheric Environment*, 201, 148–157, 2019.

Shen, X., Sun, J., Ma, Q., Zhang, Y., Zhong, J., Yue, Y., Xia, C., Hu, X., Zhang, S., and Zhang, X.: Long-term trend of new particle formation events in the Yangtze River Delta, China and its influencing factors: 7-year dataset analysis, *Science of The Total Environment*, 807, 150783, 2022.

Singh, K., Gautam, A. S., Jeni Victor, N., Kumar, S., Potdar, S. S., Komsaare, K., and Siingh, D.: Characteristics of new particle formation events at high-altitude location of Western Himalayan Region, Tehri Garhwal, India, *Atmospheric Research*, 315, 107903, <https://doi.org/10.1016/j.atmosres.2024.107903>, 2025.

Tang, L., Hu, M., Shang, D., Fang, X., Mao, J., Xu, W., Zhou, J., Zhao, W., Wang, Y., Zhang, C., Zhang, Y., Hu, J., Zeng, L., Ye, C., Guo, S., and Wu, Z.: High frequency of new particle formation events driven by summer monsoon in the central Tibetan Plateau, China, *Atmos. Chem. Phys.*, 23, 4343–4359, 10.5194/acp-23-4343-2023, 2023.

Venzac, H., Sellegri, K., Laj, P., Villani, P., Bonasoni, P., Marinoni, A., Cristofanelli, P., Calzolari, F., Fuzzi, S., Decesari, S., Facchini, M.-C., Vuillermoz, E., and Verza, G. P.: High frequency new particle formation in the Himalayas, *Proceedings of the National Academy of Sciences*, 105, 15666–15671, 10.1073/pnas.0801355105, 2008.

Victor, J. N., Buchunde, P., Sebastian, M., Kanawade, V. P., Siingh, D., Mukherjee, S., Potdar, S. S., Dharmaraj, T., and Pandithurai, G.: Characteristics of new particle formation events in a mountain semi-rural location in India, *Atmospheric Environment*, 324, 120414, <https://doi.org/10.1016/j.atmosenv.2024.120414>, 2024.

Wang, J., Li, M., Li, L., Zheng, R., Fan, X., Hong, Y., Xu, L., Chen, J., and Hu, B.: Particle number size distribution and new particle formation in Xiamen, the coastal city of Southeast China in wintertime, *Science of The Total Environment*, 826, 154208, <https://doi.org/10.1016/j.scitotenv.2022.154208>, 2022.

Wu, H., Li, Z., Jiang, M., Liang, C., Zhang, D., Wu, T., Wang, Y., and Cribb, M.: Contributions of traffic emissions and new particle formation to the ultrafine particle size distribution in the megacity of Beijing, *Atmospheric Environment*, 262, 118652, <https://doi.org/10.1016/j.atmosenv.2021.118652>, 2021.

628 Wu, H., Li, Z., Hai, S., Gao, Y., Jiang, J., Zhao, B., Cribb, M., Zhang, D., Pu, D., Liu, M., Wang, C., Lan, J., and Wang, Y.:
 629 Vertical transport of ultrafine particles and turbulence evolution impact on new particle formation at the surface & Canton
 630 Tower, *Atmospheric Research*, 302, 10.1016/j.atmosres.2024.107290, 2024.
 631 Yang, C., Brean, J., Xu, W., Xu, L., Huang, W., Fan, X., Bianchi, F., Du, W., Lin, Z., Li, L., Chen, G., Zhang, Y., Cai, R.,
 632 Chen, Y., Li, M., and Chen, J.: Anthropogenic Oxygenated Organic Molecules Dominate New Particle Growth in Moderate-
 633 Pollution Urban China, *Environ Sci Technol*, 60, 6364–6377, 10.1021/acs.est.5c11555, 2026.
 634 Yao, L., Garmash, O., Bianchi, F., Zheng, J., Yan, C., Kontkanen, J., Junninen, H., Mazon, S. B., Ehn, M., and Paasonen, P.:
 635 Atmospheric new particle formation from sulfuric acid and amines in a Chinese megacity, *Science*, 361, 278–281, 2018.
 636 Yeganeh, B., Shakerdonyavi, A., Zafarmomen, N., and Taheri, A.: Comprehensive spatiotemporal analysis of long-term
 637 mobile monitoring for traffic-related particles in a complex urban environment, *Atmospheric Pollution Research*, 17, 102870,
 638 <https://doi.org/10.1016/j.apr.2025.102870>, 2026.
 639 Zhang, K., Xu, Z., Zhang, F., and Wang, Z.: Unveiling the organic contribution to the initial particle growth in 3–10 nm size
 640 range, *Atmospheric Chemistry and Physics*, 26, 2241–2254, 10.5194/acp-26-2241-2026, 2026.
 641 Zhang, Q., Jia, S., Yang, L., Krishnan, P., Zhou, S., Shao, M., and Wang, X.: New particle formation (NPF) events in China
 642 urban clusters given by severe composite pollution background, *Chemosphere*, 262, 127842,
 643 <https://doi.org/10.1016/j.chemosphere.2020.127842>, 2021.
 644 Zhao, W., Zhang, X., Zhai, L., Shen, X., and Xu, J.: Chemical characterization and sources of submicron aerosols in Lhasa
 645 on the Qinghai–Tibet Plateau: Insights from high-resolution mass spectrometry, *Science of the Total Environment*, 815,
 646 152866, 2022.
 647