

# Seasonal variation in aerosol chemistry drives new particle formation and CCN activity in a coastal city, China: insights from year-long online measurements in Fuzhou

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**Abstract:** New particle formation (NPF) is an important source of cloud condensation nuclei (CCN), which affects the global climate. Continuous observations in the coastal city of Fuzhou, conducted from June 2021 to May 2022, aimed to study NPF events and their impact on CCN. A total of 46 NPF events were identified, with a frequency of 12.7 %. The average formation rate (FR) and growth rate (GR) of particles were  $3.94 \pm 8.26 \text{ cm}^{-3} \cdot \text{s}^{-1}$  and  $5.20 \pm 1.78 \text{ nm} \cdot \text{h}^{-1}$ . The NPF events showed evident seasonal variation: spring (27.17%), fall (9.89%), winter (8.89%), and summer (4.35%). Spring NPF events were characterized by high FR ( $5.56 \text{ cm}^{-3} \cdot \text{s}^{-1}$ ) and suppressed growth processes, while summer, under the dominance of marine winds, exhibited the lowest FR yet the highest GR among all seasons (peak value  $11.68 \text{ nm} \cdot \text{h}^{-1}$ ). The influence of NPF on the chemical composition of  $\text{PM}_{2.5}$  and CCN also showed seasonal differences. In summer, NPF generated substantial amounts of sulfate and nitrate, resulting in stronger particle hygroscopicity ( $> 0.6$ ). In fall and winter, higher concentrations of black carbon (BC) and primary organic carbon (POC) led to weaker  $K_{\text{inorg}}$  ( $\leq 0.55$ ). XGBoost-SHAP attribution further quantified that FR is dominated by physical processes (nucleation mode 76.2 %, CS 13.8 %), with a sharp  $\text{NH}_3$  threshold at  $4 \mu\text{g m}^{-3}$  and a narrow temperature range (20–25 °C). For particle growth, temperature shows a linear positive effect above 20°C, and RH  $> 60$  % consistently suppresses particle concentrations.

32 The enhancement effect of NPF on CCN was most significant in summer ( $E_{N_{CCN}} = 1.64$ ), accompanied  
33 by CCN growth. In spring, the high condensation sink (CS) suppressed growth, leading to an insignificant  
34 CCN enhancement effect. In fall and winter, NPF-induced CCN enhancement mainly occurred 3–5 hours  
35 after the event, with increases ranging from 13% to 65%, particularly notable at high supersaturation  
36 levels (0.8–1.0% SS).

## 37 **1 Introduction**

38 New particle formation (NPF) is a complex process in which gaseous precursors in the atmosphere  
39 nucleate and condense to form new particles, which subsequently grow through condensation,  
40 coagulation, and other processes. NPF contributes over 50 % of the global cloud condensation nuclei  
41 (CCN), significantly influencing cloud albedo, structure, lifetime, and solar radiation reaching the Earth's  
42 surface (Tröstl et al., 2016; Yao et al., 2018). Additionally, efficient nucleation and explosive growth of  
43 particles are important sources of haze formation in urban atmospheres, impacting air quality and public  
44 health (Kulmala et al., 2021).

45 Although its frequency may vary with season and location, NPF events fundamentally represent  
46 competition between aerosol particle sources and sinks. Current research indicates that secondary particle  
47 formation is driven by the photochemical oxidation of atmospheric gases. Sulfuric acid and highly  
48 oxidized molecules can act as nucleation precursors (Fan et al., 2018; Zaveri et al., 2022). Furthermore,  
49 ions may also play a role in particle nucleation, though their significance remains debated (Hirsikko et  
50 al., 2011; Kirkby et al., 2016). Pre-existing aerosol particles act as a sink for these precursors, small  
51 clusters, and newly formed particles, thereby suppressing NPF occurrence (McMurry and Friedlander,  
52 1979). However, frequent NPF events also occur in heavily polluted cities (Sun et al., 2015; Yao et al.,  
53 2018). Therefore, the mechanisms governing NPF generation and growth under different atmospheric  
54 conditions are still under investigation.

55 NPF events can be described by the formation rate (FR) of nucleation-mode particles and the growth rate  
56 (GR) of newly formed particles (Kulmala et al., 2012). The formation rate of 3 nm particles in the  
57 boundary layer typically ranges from 0.01 to 10  $\text{cm}^{-3}\cdot\text{s}^{-1}$ , while the typical growth rate in mid-latitudes  
58 ranges from 1 to 20  $\text{nm h}^{-1}$  (Kulmala et al., 2004). Yli-Juuti et al. (2011) reported typical growth rates of

59 1.8–10.7 nm·h<sup>-1</sup> for 1.5–20 nm particles. Previous studies have shown that NPF is enhanced in the  
60 presence of sulfuric acid, alkaline substances, organic acids, and ions (Wang et al., 2011) but suppressed  
61 in the presence of nitrogen oxides (NO<sub>x</sub>) (Wildt et al., 2014), indicating significant synergistic effects in  
62 chemically complex mixtures (Guo et al., 2014). The availability of precursor vapors and the atmospheric  
63 chemical environment play decisive roles. H<sub>2</sub>SO<sub>4</sub> is a key nucleating species, and its stabilizing  
64 co-components, such as ammonia (NH<sub>3</sub>) and amines, can dramatically enhance FR (Dunne et al., 2016;  
65 Yao et al., 2018; Kirkby et al., 2016). For particle growth, condensation of low-volatility compounds is  
66 the dominant process. Sipilä et al. (2010) showed experimentally that early-stage growth is primarily  
67 driven by H<sub>2</sub>SO<sub>4</sub> condensation.

68 Additionally, NPF occurrence is constrained by atmospheric temperature and humidity (Yu et al., 2017;  
69 Yue and Hamill, 1979). Low temperatures promote nucleation, whereas high temperatures suppress it  
70 (Sipilä et al., 2010; Dunne et al., 2016; Yu et al., 2017). Dunne et al. (2016) further showed that at low  
71 temperatures, the ion-enhancement effect is weak due to suppressed evaporation of neutral clusters, while  
72 at ambient temperatures, ions can increase the nucleation rate by about a factor of 15. Consequently,  
73 neglecting temperature dependence leads to a marked overestimation of NPF and CCN concentrations in  
74 summer (Yu et al., 2017). Hamed et al. (2011), based on observations at multiple continental sites, found  
75 that NPF events predominantly occur at relative humidity below 60% and are rare above 80%. The reason  
76 is that high relative humidity reduces ultraviolet radiation, lowering the production of OH and H<sub>2</sub>SO<sub>4</sub>;  
77 meanwhile, hygroscopic growth enhances the condensation sink, thereby suppressing new particle  
78 formation.

79 Aerosol chemical composition also influences aerosol hygroscopicity, altering its critical diameter and  
80 thereby affecting CCN activation and cloud formation (Petters and Kreidenweis, 2007; Williamson et al.,  
81 2019; Xu et al., 2020). Petters and Kreidenweis (2007) proposed hygroscopicity parameter ( $\kappa$ ) is widely  
82 used to quantify the water uptake ability and CCN activity of aerosols. Extensive experimental studies  
83 have well characterized the  $\kappa$  values of inorganic salts such as ammonium sulfate, ammonium nitrate,  
84 and ammonium bisulfate (Liu et al., 2014; Kuang et al., 2020; Cai et al., 2018; Wu et al., 2016). In the  
85 accumulation mode (150–1  $\mu$ m), inorganic species contribute about 90% of the total  $\kappa$  (Liu et al., 2014).

86 Observations across different environments (e.g., mountain, urban) have shown that NPF events typically  
87 lead to a significant increase in  $N_{CCN}$  (Kuwata et al., 2008; Yue et al., 2011; Fan et al., 2018). Kuwata et  
88 al. (2008) observed a clear increase in  $N_{CCN}$  at different supersaturation levels after NPF events on Jeju  
89 Island, South Korea. Research in Beijing indicated that NPF events could increase local  $N_{CCN}$  by 0.4–6  
90 times (Yue et al., 2011). In polluted environments, additional condensable species, particularly  
91 ammonium nitrate and secondary organic aerosols, can accelerate growth and shorten the time needed  
92 for freshly formed particles to reach CCN-active sizes (Zhu et al., 2026). However, some studies suggest  
93 that an increase in hydrophobic organic components during subsequent particle growth may inhibit CCN  
94 generation. Therefore, understanding the role of different components during particle growth is crucial  
95 for assessing their subsequent climate effects.

96 Although NPF research in China is widespread, most studies focus on reporting occurrence frequencies,  
97 formation, and growth rates, or are limited to discussing nucleation mechanisms. For instance, NPF event  
98 frequencies at sites like Shangdianzi, Mount Tai, and Lin'an in eastern China range from 15% to 29%  
99 (Shen et al., 2018). Frequencies in Beijing, Jinan, and Shanghai are approximately 30%, 40%, and 21%,  
100 respectively (Jayaratne et al., 2017; Lv et al., 2018; Xiao et al., 2015). Currently, understanding how  
101 regional variations in atmospheric oxidants and precursors affect the growth of newly formed particles  
102 to CCN sizes, especially the quantification of their CCN efficiency, remains a challenge and frontier in  
103 current research (Cai et al., 2018; Kulmala et al., 2021; Rose et al., 2017; Xiao et al., 2015; Yao et al.,  
104 2018). Given that Fuzhou is a rapidly developing southeastern coastal city with unique sea-land breeze  
105 conditions, a high-temperature and high-humidity environment, and complex pollution emission  
106 characteristics, it may have unique NPF mechanisms. However, there is a lack of long-term  
107 comprehensive observation or systematically quantified NPF's CCN efficiency in this region. Therefore,  
108 this study conducted a one-year comprehensive observation in Fuzhou from June 2021 to May 2022,  
109 providing new insights and data support for understanding the CCN efficiency and potential climate  
110 relevance of NPF under China's complex atmospheric environment.

## 111 **2 Data and Methods**

### 112 **2.1 Observation site**

113 Observation data for this study were collected from June 1, 2021, to May 30, 2022, during comprehensive  
114 atmospheric environmental observations conducted at the Fujian Provincial Environmental Monitoring  
115 Center Station (26.11°N, 119.30°E, altitude 65 m) and the Fuzhou Meteorological Bureau Station  
116 (26.05°N, 119.26°E, altitude 18 m). Both stations are located within Fuzhou's urban area, approximately  
117 8 km apart horizontally. The Fujian Provincial Environmental Monitoring Center Station is situated in  
118 Gulou District, the central urban area of Fuzhou, surrounded primarily by commercial, residential, and  
119 transportation land, representing areas heavily influenced by intense human activities. The Fuzhou  
120 Meteorological Bureau Station is located in Cangshan District, southern Fuzhou, approximately 1.5 km  
121 east of the Min River. Fuzhou is situated at the Min River estuary and along the East China Sea coast,  
122 characterized mainly by plains (average altitude 10–30 m) and a typical East Asian monsoon climate,  
123 significantly influenced by sea-land breeze circulation and marine air masses (Hu et al., 2024). Given the  
124 short distance (~8 km) and the regional background homogeneity, the local environments of the two sites  
125 are not expected to be drastically different, although each is influenced by its specific surroundings (urban  
126 vs. riverside). A comparison of air pollutant concentrations between the two sites using nearby national  
127 monitoring stations (Table S2).

### 128 **2.2 Measurement and instrumentation**

129 A CCN counter (CCN-100; DMT, USA) equipped with a continuous flow of 500 cm<sup>3</sup>/min and a thermal  
130 gradient was used to measure CCN concentrations at five supersaturation (SS) levels. To maintain  
131 counting accuracy, the instrument was regularly calibrated for T gradient, flow rate, pressure, SS, and  
132 the optical particle counter (OPC) using standard ammonium sulfate according to the method by Rose et  
133 al. (2008). Additionally, zero-point determination was performed before and after each observation to  
134 minimize instrumental error. During observations, the measurement interval for each SS level was 10  
135 minutes, and a few minutes were required to stabilize after switching SS levels. Therefore, CCN data  
136 collected before reaching stable SS were excluded from subsequent analysis. The typical measurement  
137 uncertainty of the CCN-100 is approximately ±10% in Table S1.

138 An online organic carbon/elemental carbon analyzer (Sunset Laboratory semicontinuous OC/EC  
139 analyzer, Model-4, Sunset Laboratory Inc., USA) was used to determine organic carbon (OC) and  
140 elemental carbon (EC) content in atmospheric particulate matter samples. The instrument provides hourly  
141 averaged concentrations. Details of instrument operation can be found in Chang et al. (2017). Based on  
142 replicate analyses reported by Zhang et al. (2021), the within-model measurement uncertainties (relative  
143 standard deviation) for the Sunset Model-4 are  $\pm 3.6\%$  for OC and  $\pm 6.8\%$  for EC.

144 A Wide-Range Particle Spectrometer (WPS-1000, MSP) measured aerosol number size distributions (10-  
145 350 nm) with a time resolution of 6 minutes across 96 channels. To align with the 1-hour meteorological  
146 data, the 6-minute distributions were arithmetically averaged to hourly particle number size distributions.  
147 Instrument details and principles are described in Wang et al. (2014). The typical uncertainty for particle  
148 size distribution measurements in this size range is approximately  $\pm 10\%$  in Table S1.

149 Black carbon (BC) mass concentration was measured using an Aethalometer (AE-33, Magee Scientific)  
150 with a time resolution of 1 hour. BC data from the 880 nm wavelength (channel 6) were used (Kirchstetter  
151 et al., 2004). The measurement uncertainty is approximately  $\pm 10\%$  (Table S1).

152 An online particle chromatograph (MARGA ADI-2080) continuously monitored mass concentrations of  
153 soluble aerosol ionic components ( $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ) and trace gases ( $\text{NH}_3$ ,  $\text{HNO}_2$ ,  
154  $\text{HNO}_3$ ,  $\text{HCl}$ ,  $\text{SO}_2$ ). Sampling, operation, and internal calibration methods followed Du et al. (2011). The  
155 instrument provides hourly averaged concentrations. According to an independent verification study  
156 (Battelle, 2009), the measurement precision (median absolute relative percent difference between  
157 duplicate units) ranges from 5% for  $\text{SO}_2$  to 20% for  $\text{NH}_4^+$ , with data completeness  $>90\%$  for all major  
158 ions.

159 Meteorological data (including wind speed (WS), wind direction (WD), temperature (T), relative  
160 humidity (RH), and precipitation) with a time resolution of 1 h were obtained from the Fuzhou Olympic  
161 Sports Center Meteorological Station. Data on conventional air pollutants ( $\text{O}_3$ ,  $\text{CO}$ ,  $\text{NO}_2$ ,  $\text{PM}_{2.5}$ , and  $\text{PM}_{10}$ )  
162 were sourced from the China National Environmental Monitoring Centre's real-time urban air quality  
163 release platform (<https://quotsoft.net/air/>).

### 164 **2.3 Analysis methods**

165 The growth rate (GR) of new particles was calculated following (Kulmala et al., 2012):

166 
$$GR = \frac{\Delta D_m}{\Delta t} \quad (1)$$

167 where  $D_m$  is the median diameter of the nucleation mode particles, obtained by fitting a log-normal  
 168 distribution to the particle number size distribution. Statistics of the fitting results (see Supplementary  
 169 Material) demonstrate that the log-normal distribution represents the observed particle size distributions  
 170 well, with the majority of fits yielding high coefficients of determination ( $R^2 > 0.85$ ); only fits with  $R^2 > 0.7$   
 171 were used to avoid propagating poor-fitting uncertainties. GR describes how rapidly particles grow from  
 172 the nucleation size to larger sizes. It is later used to estimate the formation rate of new particles (Eq. 2)  
 173 and condensable vapor concentration (Eq. 4) and to evaluate the competition between condensation and  
 174 coagulation during NPF events.

175 The condensation sink (CS) reflects the rate at which condensable vapor molecules condense onto the  
 176 surface of pre-existing atmospheric particles and was calculated as follows (Kulmala et al., 2012):

177 
$$CS = 4\pi D \sum_i \beta_{M,i} \cdot D_i \cdot N_i \quad (2)$$

178 where  $D$  is the diffusion coefficient of the vapor (typically assumed to be sulfuric acid),  $N_i$  is the number  
 179 concentration of particles in a given size bin, and  $\beta_M$  is a correction factor.

180 The coagulation sink (CoagS) reflects the ability and rate of pre-existing atmospheric particles to remove  
 181 newly formed nucleation particles via coagulation. For particles of size  $i$ , the coagulation sink can be  
 182 expressed as:

183 
$$CoagS_i = \sum_j K_{ij} N_j \quad (3)$$

184 where  $N_j$  is the number concentration of particles in size bin  $j$ , and  $K_{ij}$  is the Brownian coagulation  
 185 coefficient between particles of size  $j$  and  $i$ .

186 The formation rate (FR) of new particles was calculated following Kulmala et al. (2012):

187 
$$FR = \frac{dN_{nuc}}{dt} + CoagS_{nuc} \cdot N_{nuc} + \frac{GR}{\Delta dp} + S_{losses} \quad (4)$$

188 where  $N_{nuc}$  is the number concentration of nucleation-mode particles. Following the definition by  
 189 Kulmala et al. (2012), the nucleation-mode size range in this study was also limited to below 25 nm.  
 190  $CoagS_{nuc} N_{nuc}$  is the flux of particles lost due to coagulation with pre-existing particles, where  $CoagS_{nuc}$   
 191 is the coagulation sink for nucleation-mode particles.  $GR/\Delta dp$  represents the flux of particles growing  
 192 out of the nucleation size range (exceeding 25 nm), which is generally negligible under typical

193 atmospheric conditions (Dal Maso et al., 2005). FR is later used to compare NPF event intensity under  
194 different meteorological and chemical conditions, and to identify periods with active nucleation. The  
195 additional loss term  $S_{\text{losses}}$  (e.g., dilution due to boundary layer growth, wall losses) was negligible under  
196 our field conditions (Dal Maso et al., 2005). For regional NPF events, transport losses can also be ignored.  
197 FR is a direct measure of NPF intensity and is later compared across different meteorological and  
198 chemical conditions.

199 Condensable vapor concentration (C) and source rate (Q). Assuming that particle growth is dominated  
200 by condensation of a low-volatility vapor (typically sulfuric acid), the vapor concentration can be  
201 estimated from the observed growth rate (Dal Maso et al., 2005; Kulmala et al., 2012):

$$202 \quad C = A \times \frac{dD_p}{dt} \quad (5)$$

203 where  $D_p$  is the particle diameter, and  $A$  is a constant, which has the value  $1.37 \times 10^{-7} \text{ h} \cdot \text{cm}^{-3} \cdot \text{nm}^{-1}$  for a  
204 vapor with molecular properties of sulfuric acid (Dal Maso et al., 2005). This provides an upper-limit  
205 estimate of the condensable vapor concentration, as it assumes growth is solely due to condensation of  
206 the vapor and neglects contributions from coagulation.

207 The CS (Eq. 2) quantifies the rate at which this vapor is removed by pre-existing particles. Under  
208 steady-state conditions ( $dC/dt=0$ ), the vapor source rate  $Q$  can be derived as (Dal Maso et al., 2005):

$$209 \quad Q = CS \times C \quad (6)$$

210 This source rate represents the net production of condensable vapor needed to maintain the observed  
211 growth and is later compared with precursor gas concentrations (e.g.,  $\text{SO}_2$ ) to infer the chemical pathways  
212 driving NPF.

213 Hygroscopicity parameter ( $\kappa_{\text{inorg}}$ ) for inorganic species. Due to the lack of organic composition  
214 measurements, we estimated the hygroscopicity of the inorganic fraction only. The measured  
215 water-soluble ions ( $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{Cl}^-$ ) were converted to mass concentrations of inorganic salts  
216 using the ion-pairing scheme described in Gysel et al. (2007) and Kuang et al. (2020). The following  
217 salts and their  $\kappa$  values (Kuang et al., 2020, Table S2) were considered:  $(\text{NH}_4)_2\text{SO}_4$  ( $\kappa = 0.48$ ),  $\text{NH}_4\text{NO}_3$   
218 ( $\kappa = 0.58$ ),  $\text{NH}_4\text{HSO}_4$  ( $\kappa = 0.56$ ), and  $\text{NH}_4\text{Cl}$  ( $\kappa = 0.93$ ). The volume fraction of each salt was calculated  
219 using its density (also from Kuang et al., 2020). The overall inorganic hygroscopicity parameter  $\kappa_{\text{inorg}}$   
220 was then obtained by volume-weighted mixing (Petters and Kreidenweis, 2007):

$$\kappa_{inorg} = \sum_i \varepsilon_i \kappa_i \quad (7)$$

where  $\kappa_i$  and  $\varepsilon_i$  represent the hygroscopicity parameter and volume fraction of component  $i$  in the mixture, respectively, and  $i$  denotes the number of components. This  $\kappa_{inorg}$  represents the hygroscopicity of the inorganic aerosol components and is used as an upper limit estimate for the total particle hygroscopicity, as organic matter (typically less hygroscopic) was not included.

The concentrations of secondary organic carbon (SOC) and primary organic carbon (POC) were estimated following (Wu and Yu, 2016):

$$POC = (OC/EC)_{min} \times EC \quad (8)$$

$$SOC = OC_{total} - (OC/EC)_{pri} \times EC \quad (9)$$

where  $OC_{total}$  is the measured OC,  $(OC/EC)_{min}$  is the minimum (OC/EC) ratio during the observation period, POC is primary organic carbon, and SOC is secondary organic carbon.

The enhancement effect on cloud condensation nuclei number concentration ( $E_{N_{CCN}}$ ) was defined as the ratio of CCN number concentration after the NPF event to that before the event (Ren et al., 2021):

$$E_{N_{CCN}} = N_{CCN, after} / N_{CCN, prior} \quad (10)$$

where  $N_{CCN, after}$  is the average CCN number concentration during the NPF event (from its start to end), and  $N_{CCN, prior}$  is the average CCN concentration during the 2 h before the event. This factor directly links NPF to potential cloud formation: a value  $>1$  indicates that NPF increases CCN availability.

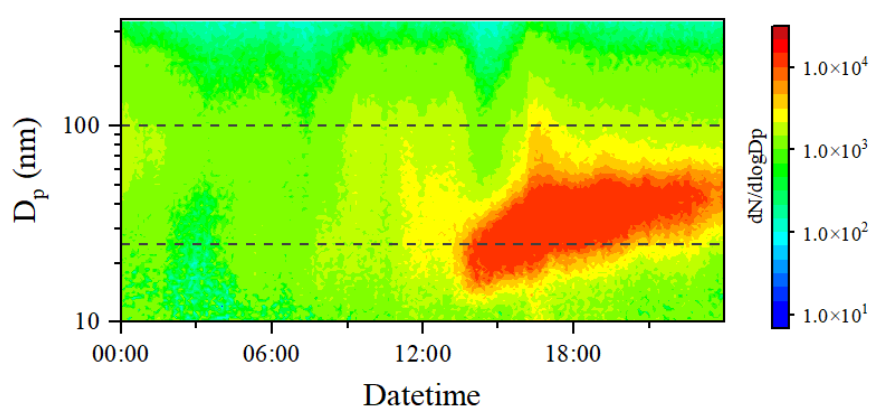
XGBoost-SHAP framework. To quantitatively evaluate the nonlinear effects of meteorological factors (T, RH) and precursor gases ( $NH_3$ ,  $SO_2$ ) on the particle formation rate (FR), we applied an interpretable machine learning framework combining XGBoost (Extreme Gradient Boosting) with SHAP (SHapley Additive exPlanations). A detailed description of the feature selection, model training, validation, and SHAP interpretation is provided in the supplementary material (Text S1). The main quantitative thresholds and interaction strengths derived from this analysis are discussed in Section 3.4.

## 2.4 Identification of NPF events

NPF events were identified based on criteria from Kulmala et al. (2012): (1) significant increase in nucleation-mode number concentration ( $N_{nuc}$ ) (diameter 10–25 nm); (2) formation of a new mode lasting several hours; (3) growth of the newly formed mode over several hours. Additional criteria for NPF

248 identification included: low pre-existing particle number concentration, a clear "banana-shaped"  
249 evolution in particle number concentration over time and size, and exclusion of interference from pre-  
250 existing particles (especially in urban environments) (Heintzenberg et al., 2007).

251 In this study, a day was defined as an effective NPF day if the nucleation-mode (10–25 nm) particle  
252 number concentration increased continuously for at least 2 h from its initial value to its maximum and  
253 showed clear growth to larger sizes (e.g., 12–50 nm) over several hours (Fig. 1). Other days were defined  
254 as non-NPF days (Leng et al., 2014). During the one-year observation, a total of 46 NPF events and 319  
255 non-NPF days were identified.



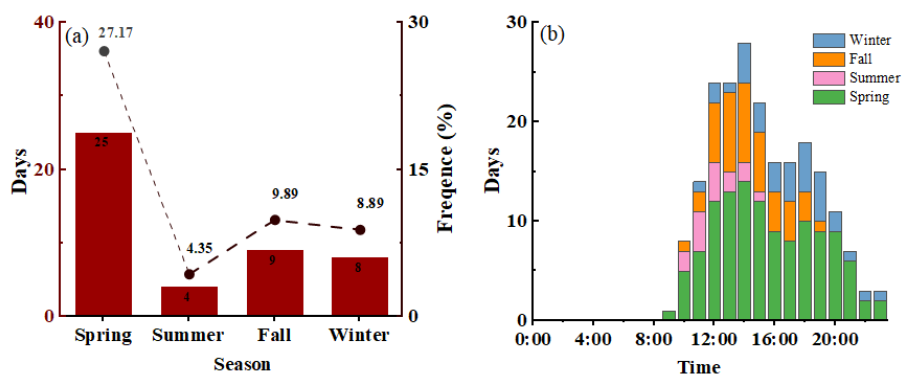
256

257 **Fig. 1** An example NPF event observed on 21 April 2022.

### 258 **3 Results and Discussion**

#### 259 **3.1 Overall characteristics of NPF occurrence**

260 NPF events in Fuzhou exhibited a distinct seasonal preference. As shown in Fig. 2a, spring was the  
261 season with the highest NPF frequency (27.17 %), while summer had the lowest (4.35 %). Fall (9.89 %)  
262 and winter (8.89 %) showed intermediate to low frequencies. NPF events mainly occurred between 9:00  
263 and 12:00.



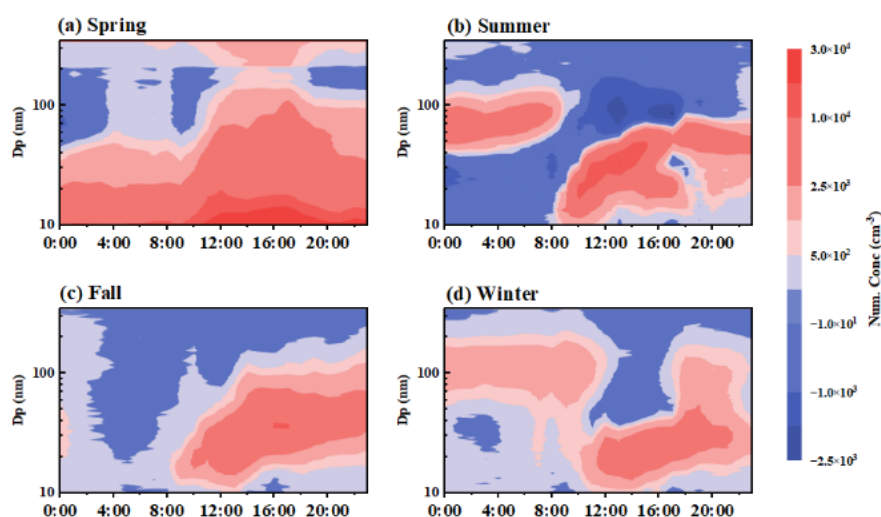
**Fig. 2 The occurrence frequency and diurnal distribution of NPF events.**

NPF events led to significant increases in nucleation-mode ( $N_{nuc}$ ) and Aitken-mode ( $N_{ait}$ ) particle number concentrations (Fig. S1). Spring showed the highest increase in  $N_{nuc}$  (196.7%), while fall showed the highest increase in  $N_{ait}$  (70.5%), indicating differences in new particle formation and subsequent growth across seasons.

NPF days typically corresponded to a lower background of  $PM_{2.5}$  and  $PM_{10}$  (Fig.S3), indicating that NPF occurred in relatively clean atmospheres with a weak condensation sink. It should be noted that the absolute  $PM_{2.5}$  and  $PM_{10}$  in winter and spring were still relatively high compared to other seasons (Fig.S3), implying that even on NPF days. In spring, summer, and winter, POC on NPF days were lower than on non-NPF days, corroborating this point. Meanwhile, in spring, summer, and fall, SOC was higher on NPF days, suggesting that secondary organic vapors may actively participate in particle formation and growth.

Although spring and winter had heavy background pollution, Fig.S4 shows that the gaseous precursor  $SO_2$  concentration on NPF days was significantly higher than on non-NPF days (winter:  $0.88$  vs.  $0.76 \mu g \cdot m^{-3}$ ; spring:  $0.64$  vs.  $0.53 \mu g \cdot m^{-3}$ ). This indicates that in polluted seasons, high gaseous precursors can overcome the inhibitory effect of a high CS and thus trigger nucleation. In contrast, NPF days in summer and Fall exhibited a distinctly clean background, with  $NH_3$  and  $HNO_2$  significantly lower than on non-NPF days (Fig.S4). In summer, fall, and winter, the concentrations of sulfate ( $SO_4^{2-}$ ), nitrate ( $NO_3^-$ ), and ammonium ( $NH_4^+$ ) on NPF days were significantly lower than on non-NPF days (Fig.S5). This suggests that in these seasons, the lower pre-existing particles and the reduced CS lessen the consumption of gaseous precursors, thereby favouring new particle formation and subsequent growth. However, spring presents a special case in that the SNA (sulfate, nitrate, and ammonium) concentrations on NPF days

287 were comparable to those on non-NPF days ( $\text{SO}_4^{2-}$ : 4.35 vs. 4.27  $\mu\text{g}\cdot\text{m}^{-3}$ ). This indicates that spring NPF  
 288 events are driven by high precursor concentrations. Even when the background particle level is high, the  
 289 abundant supply of gaseous precursors (Fig. S4) can still overcome the inhibition and trigger NPF events.  
 290 According to the hygroscopicity parameter ( $\kappa_{\text{inorg}}$ ) shown in Fig. S6, the  $\kappa_{\text{inorg}}$  values on NPF days were  
 291 generally lower than on non-NPF days in all seasons except summer, which is generally attributed to an  
 292 increased proportion of weakly hygroscopic components in newly formed particles. However, the  $\kappa_{\text{inorg}}$   
 293 on NPF days was significantly higher than on non-NPF days in summer. Combined with the higher  $\text{Cl}^-$   
 294 concentration on summer NPF days in Fig. S5 (0.59 vs. 0.28  $\mu\text{g}\cdot\text{m}^{-3}$ ). Despite reduced hygroscopicity,  
 295 NPF events effectively increased  $N_{\text{CCN}}$ . At  $\text{SS}$  above 0.4 %,  $N_{\text{CCN}}$  on NPF days was higher than on non-  
 296 NPF days in all seasons except spring, with the most significant increases observed in winter and fall  
 297 (Fig.S7).



298  
 299 **Fig. 3 The differences in particle number size distributions between NPF days and non-NPF days for each**  
 300 **season.**

301 Fig. 3a shows that in spring, particle number concentrations in the 10–20 nm range are generally elevated.  
 302 NPF typically occurs from 9:00 to 20:00, with the peak concentration of 10–15 nm particles reaching  
 303 29,498  $\text{cm}^{-3}$ . Concurrently, the concentration of particles  $>20$  nm increases significantly, with some  
 304 growing beyond 100 nm. The aerosol size distributions on NPF days in summer, fall, and winter all  
 305 exhibit an NPF process pattern similar to that shown in Fig. 1, typically occurring in 09:00–20:00. During  
 306 summer NPF events, the maximum particle number concentration reaches approximately 11,410  $\text{cm}^{-3}$ ,  
 307 with particles growing up to around 50 nm. In fall and winter, peak particle number concentrations are

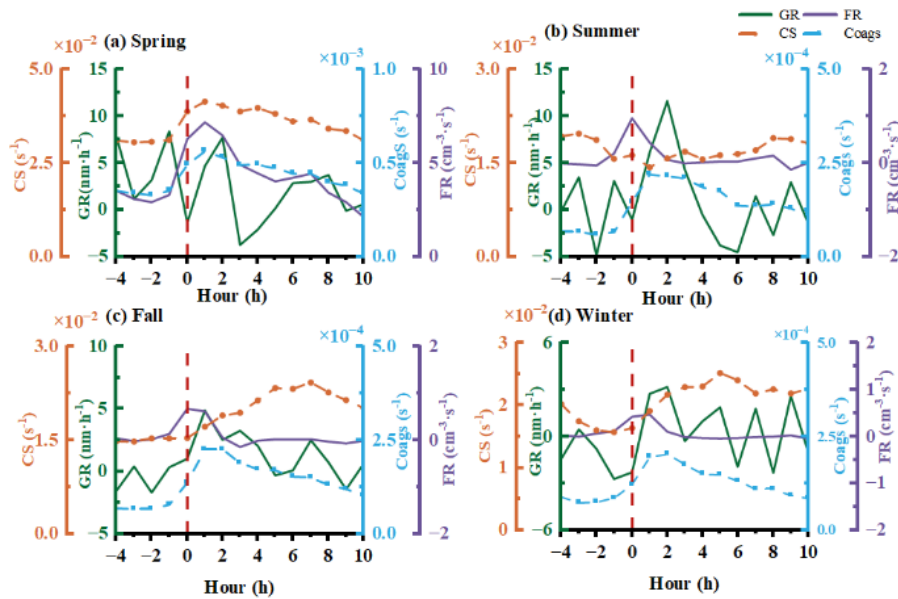
308 lower than in summer (10110 and 5276 cm<sup>-3</sup>), indicating weaker NPF intensity, and the maximum  
 309 particle growth can extend up to 100 nm in these seasons.

### 310 3.2 Evolution characteristics and key parameters of NPF events

311 Spring NPF events had the highest formation rate (FR=7.13 cm<sup>-3</sup>·s<sup>-1</sup>) and the highest condensation sink  
 312 (CS=4.1×10<sup>-2</sup> s<sup>-1</sup>) among all seasons (Table 1). Before NPF events (-4 to 0 h), N<sub>nuc</sub> increased from 5425  
 313 to 7701 cm<sup>-3</sup>, peaking at 1 h (8840 cm<sup>-3</sup>), then gradually declining. This trend was consistent with changes  
 314 in the FR (Fig. 4a). FR rose sharply to 6.31 cm<sup>-3</sup>·s<sup>-1</sup> at the onset of NPF (0 h) and peaked at 7.21 cm<sup>-3</sup>·s<sup>-1</sup>  
 315 at 1 h, demonstrating strong new particle formation capability. However, intense competition under a  
 316 high CS background significantly suppressed subsequent growth. The growth rate (GR) exhibited large  
 317 fluctuations, reverting to a negative value at 3 h after an initial peak. N<sub>ait</sub> increased by only 32 % from 0  
 318 h to its peak at 2 h, much lower than in other seasons. Spring NPF events were characterized by strong  
 319 formation but suppressed growth under high CS.

320 **Table 1. Seasonal variations in key parameters of NPF events: particle growth rate (GR), formation rate (FR),**  
 321 **coagulation sink (CoagS), condensable vapor concentration (C) and its production rate (Q), condensation sink**  
 322 **(CS), and hygroscopicity parameter (κ).**

Average	FR (m <sup>-3</sup> ·s <sup>-1</sup> )	GR (nm·h <sup>-1</sup> )	CS (×10 <sup>-2</sup> ·s <sup>-1</sup> )	CoagS (×10 <sup>-4</sup> s <sup>-1</sup> )	C (×10 <sup>7</sup> cm <sup>-3</sup> )	K <sub>inorg</sub>
Total	3.94	5.20	3.1	3.9	16.7	0.56
Spring	7.13	3.69	4.1	5.2	20.1	0.54
Summer	0.40	4.20	1.8	2.0	10.9	0.59
Fall	0.28	2.35	2.0	1.8	9.5	0.55
Winter	0.23	1.87	2.1	1.9	4.7	0.58



323 **Fig. 4 Key NPF parameters: growth rate (GR), formation rate (FR), condensation sink (CS), and coagulation**  
 324 **sink (CoagS) for each season. The NPF events in each season have been normalized. The x-axis represents**  
 325 **time relative to the NPF event start, where t=0 h is the onset time (defined as the time when the**  
 326 **nucleation-mode particle number concentration begins a sustained increase). Negative times indicate hours**  
 327 **before the start, and positive times indicate hours after the start. The time axis ranges from -4 h to 10 h,**  
 328 **showing the evolution from 4 hours before to 10 hours after the event.**  
 329

330 Despite the low average FR ( $0.40 \text{ cm}^{-3}\cdot\text{s}^{-1}$ , Table 1), summer exhibited the highest average GR ( $4.20$   
 331  $\text{nm}\cdot\text{h}^{-1}$ ), and the lowest average CS ( $1.8\times 10^{-2} \text{ s}^{-1}$ ). In summer NPF events (Fig. 4b),  $N_{\text{nuc}}$  peaked at 1 h  
 332 ( $3459 \text{ cm}^{-3}$ ). FR relatively high from 0–2 h ( $0.97\text{--}0.44 \text{ cm}^{-3}\cdot\text{s}^{-1}$ ). The most prominent feature of summer  
 333 was the high growth efficiency (GR) under the lowest CS, with a maximum peak of  $11.68 \text{ nm}\cdot\text{h}^{-1}$  at 2 h.  
 334 After NPF onset in summer,  $N_{\text{ait}}$  peaked at 3 h ( $6461.6 \text{ cm}^{-3}$ ), with the highest increase of 202.91 %. This  
 335 indicates that the growth process of new particles in summer NPF events was far stronger than particle  
 336 formation.

337 Winter had the lowest average FR ( $0.23 \text{ cm}^{-3}\cdot\text{s}^{-1}$ ) and GR ( $1.87 \text{ nm}\cdot\text{h}^{-1}$ , Table 1). Winter NPF events  
 338 were characterized by a low FR and delayed growth under a low condensation sink (CS), as shown in  
 339 Table 1. In Fig.4d, the FR peak observed at 0 h ( $0.43 \text{ cm}^{-3}\cdot\text{s}^{-1}$ ) was the lowest among all seasons,  
 340 indicating weak nucleation. In contrast, the growth rate (GR) displayed a distinct multi-peak pattern, with  
 341 an initial peak at 2 h ( $3.20 \text{ nm}\cdot\text{h}^{-1}$ ) and subsequent peaks occurring between 5 and 9 h, suggesting that  
 342 different mechanisms may have driven particle growth at different stages. Correspondingly,  $N_{\text{ait}}$  reached  
 343 a maximum at 3 h ( $4794.2 \text{ cm}^{-3}$ ), which was the lowest seasonal peak (Fig.S8). Nevertheless,  $N_{\text{ait}}$

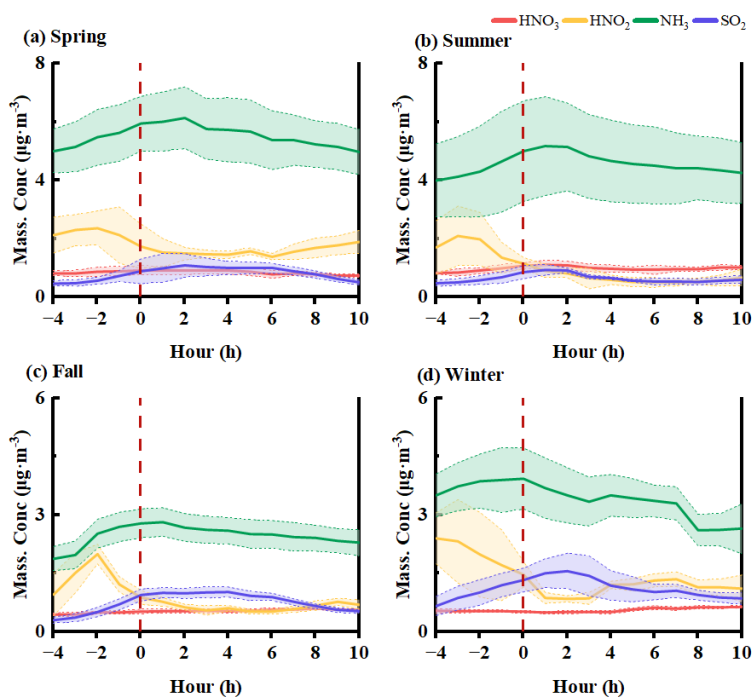
344 remained at relatively high levels ( $4500\text{--}4800\text{ cm}^{-3}$ ) over an extended period from 2 to 6 h, reflecting  
345 sustained particle growth throughout the event.

346 Fall presented transitional characteristics, with average FR ( $0.28\text{ cm}^{-3}\cdot\text{s}^{-1}$ ) and GR ( $2.35\text{ nm}\cdot\text{h}^{-1}$ ) higher  
347 than winter but lower than spring and summer (Table 1). Fall NPF process parameters showed transitional  
348 characteristics between summer and winter, generally similar to winter (Fig. 4c). Its FR peak ( $0.68\text{ cm}^{-3}\cdot\text{s}^{-1}$ ) and GR peak ( $4.90\text{ nm}\cdot\text{h}^{-1}$ ) were higher than winter but much lower than spring and summer. The  
349 increase in  $N_{\text{ait}}$  after NPF onset was 165 %, significantly stronger than in winter (Fig.S8). The  $N_{\text{ait\_peak}}$   
350 ( $6240.9\text{ cm}^{-3}$ ) occurred latest (4 h) and remained above  $5600\text{ cm}^{-3}$  from 5–7 h, higher than winter.  
351 In summary, spring shows the highest FR ( $7.13\text{ cm}^{-3}\cdot\text{s}^{-1}$ ) but the lowest GR ( $3.69\text{ nm}\cdot\text{h}^{-1}$ ) due to a large  
352 CS, indicating strong nucleation yet suppressed growth. Summer achieves the highest GR (peak  $11.68$   
353  $\text{nm}\cdot\text{h}^{-1}$ ) and the cleanest background (lowest CS), where growth dominates over formation. Fall and  
354 winter exhibit low FR and GR with delayed growth, reflecting weaker NPF intensity.

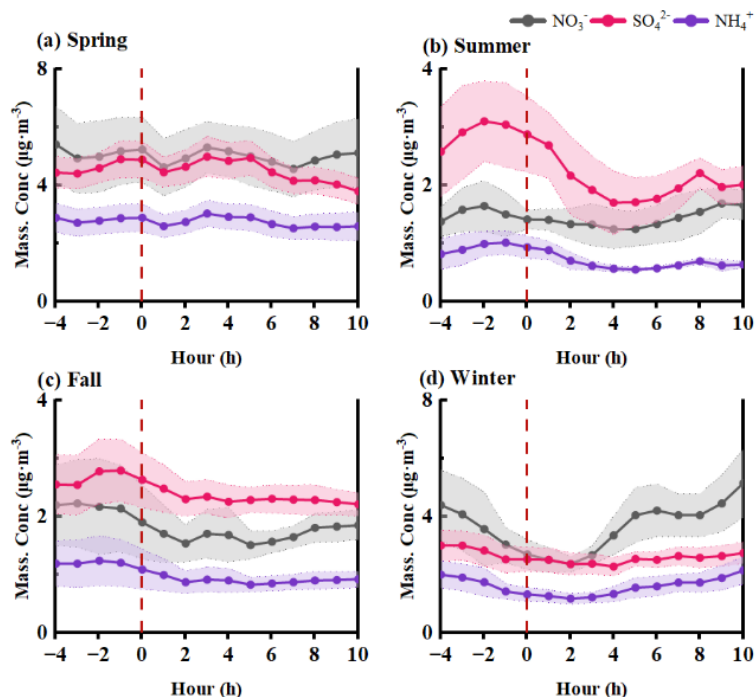
### 356 **3.3 Influence of chemical composition on NPF events**

357 Spring NPF days were characterized by the highest CS ( $4.1\times 10^{-2}\text{ s}^{-1}$ ) and were predominantly influenced  
358 by secondary pollution. Spring NPF events were mainly driven by the continuous transport from the  
359 southeast coastal pathway (CL2, 51.33%, Fig. S8a), which supplied high levels of  $\text{NH}_3$  ( $6.76\pm 2.09\text{ }\mu\text{g}\cdot\text{m}^{-3}$   
360 ) and  $\text{HNO}_2$  ( $2.81\pm 2.16\text{ }\mu\text{g}\cdot\text{m}^{-3}$ ) (Table S4). Consistently, during the NPF events, the frequency of SE/S  
361 winds continuously increased and became dominant in the later stage (maximum 38.1%), reflecting the  
362 influence of this coastal air mass at the local scale. Before NPF events, gaseous  $\text{SO}_2$  and  $\text{NH}_3$  increased  
363 from  $0.47$  and  $5.01\text{ }\mu\text{g}\cdot\text{m}^{-3}$  to  $0.89$  and  $5.95\text{ }\mu\text{g}\cdot\text{m}^{-3}$ , respectively (Fig. 5a). Two hours after NPF onset,  
364 their concentrations began to decline continuously, indicating substantial consumption. Mass  
365 concentrations of secondary inorganic salts ( $\text{SO}_4^{2-}$  and  $\text{NO}_3^-$ ) fluctuated between  $4.5\text{--}4.8\text{ }\mu\text{g}\cdot\text{m}^{-3}$  and  $4\text{--}6$   
366  $\mu\text{g}\cdot\text{m}^{-3}$ , respectively. Although  $\text{NO}_3^-$  showed minor fluctuations, it remained at relatively high levels (Fig.  
367 6a). NPF events occurred when the temperature was between  $18.9\text{--}23.2^\circ\text{C}$  (Fig. S11a), favoring  
368 accelerated photochemical reactions and gas-particle conversion of semi-volatile gases (Chen et al.,  
369 2023). Wind speeds were generally low ( $<1.9\text{ m}\cdot\text{s}^{-1}$ ), and the atmospheric stratification was stable. After  
370 NPF onset,  $\text{O}_3$  increased significantly (from  $81.1$  to  $98.8\text{ }\mu\text{g}\cdot\text{m}^{-3}$ ; Fig. S13a), indicating enhanced  
371 atmospheric oxidizability. Precursor gases ( $\text{SO}_2$  and  $\text{NO}_2$ ) were oxidized via photochemistry to form

372  $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$ , promoting the generation of secondary inorganic salts and secondary aerosols, including  
 373 secondary organic aerosol (Fig. S12a). The high CS background, spring had high-frequency and high-  
 374 FR NPF events, primarily attributed to higher precursor gas and strong photochemistry.  
 375 However, high CS competed for condensable vapors and scavenged newly formed particles, suppressing  
 376 the growth stage of new particles. Additionally, during the NPF event (1–4 h), particle hygroscopicity  
 377 decreased from 0.56 at -4 h to 0.53 (fig.S10).



378  
 379 **Fig. 5** The evolution of relevant trace gases ( $\text{SO}_2$ ,  $\text{NH}_3$ ,  $\text{NO}_2$ ) for (a) spring, (b) summer, (c) fall, and (d) winter.  
 380 The x-axis follows the same normalized time scale as defined in Fig. 4 ( $t = 0$  h represents NPF event start).  
 381 Shaded bands indicate  $\pm 1\sigma$  standard deviation



382  
 383 **Fig. 6** The evolution of major secondary inorganic ions ( $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ) for each season. The x-axis follows  
 384 the same normalized time scale as defined in Fig. 4 ( $t=0$  h represents NPF event start). Shaded bands indicate  
 385  $\pm 1\sigma$  standard deviation.

386 CS in summer, fall, and winter were relatively low (around  $2.0 \times 10^{-2} \text{ s}^{-1}$ ), indicating fewer surfaces  
 387 available for condensation in the atmosphere.

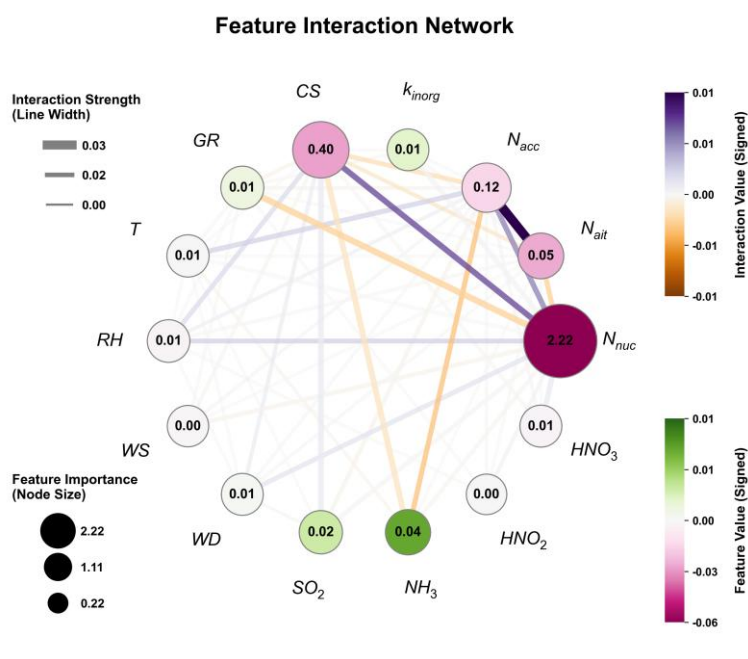
388 Summer NPF events occurred under a high-temperature environment ( $>32^\circ\text{C}$ ) (Fig. S9b), which inhibits  
 389 nucleation (Yu et al., 2017). Two hours after NPF onset (2 h), the frequency of northeasterly (NE) winds  
 390 surged from 0% (at -4 h) to 50%, corresponding to marine air mass cluster CL2 (60%), which had a low  
 391 average CS of  $1.08 \pm 0.31 \times 10^{-2} \text{ s}^{-1}$  (Table S3). The arrival of this air mass diluted local pollutants, causing  
 392  $\text{PM}_{10}$  to drop from  $14.25 \mu\text{g}\cdot\text{m}^{-3}$  at 0 h to  $8.75 \mu\text{g}\cdot\text{m}^{-3}$  at 2 h; meanwhile, it supplied abundant gaseous  
 393 precursors or enhanced local photochemical activity, leading to continuous increases in  $\text{SO}_2$  and  $\text{NH}_3$   
 394 from  $0.48$  and  $4.00 \mu\text{g}\cdot\text{m}^{-3}$  to peak values of  $0.94$  and  $5.18 \mu\text{g}\cdot\text{m}^{-3}$ , respectively, at 2 h (Fig. 5b). Therefore,  
 395 despite favorable conditions of low CS and ample sunlight, summer NPF frequency and formation rate  
 396 were low. As ozone continued to rise (0–6 h), secondary ions ( $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ) and SOC increased (Fig. 6b  
 397 and Fig. S12b). These efficiently condensed onto particle surfaces under a low CS background, achieving  
 398 extremely high growth efficiency (GR peak of  $11.59 \text{ nm}\cdot\text{h}^{-1}$ ).  $\kappa_{\text{inorg}}$  in the range of 0.61–0.75 was higher  
 399 than in other seasons, surging to 0.75 at 3 h after NPF onset. This increase was primarily driven by

400 prevailing easterly and southerly winds, corresponding to air mass cluster CL3, which had a high  $\kappa_{\text{inorg}}$   
401 (0.71). This indicates that inorganic salts of marine origin facilitated the sustained growth of particles.  
402 Before Fall NPF events,  $\text{SO}_2$  and  $\text{NH}_3$  increased from 0.36 and 1.99  $\mu\text{g}\cdot\text{m}^{-3}$  to 2.83 and 2.83  $\mu\text{g}\cdot\text{m}^{-3}$ ,  
403 respectively (Fig. 5c). This stage was dominated by northwesterly winds (NW: 62%) and strongly  
404 influenced by continental air masses from CL2 and CL3, which contributed to the initial accumulation  
405 of precursor gases ( $\text{SO}_2$  and  $\text{NH}_3$ ). The lower temperature (around 22 °C) and high humidity (RH >71 %)   
406 environment (Fig. S11c) favored the combination of sulfuric acid molecules, promoting nucleation  
407 (Lehtipalo et al., 2018; Tröstl et al., 2016; Yue and Hamill, 1979). After NPF onset, although atmospheric  
408 oxidizability increased continuously ( $\text{O}_3$  from 36 to 94  $\mu\text{g}\cdot\text{m}^{-3}$ ), it was short-lived. Within 1–3 h after  
409 NPF onset, the local wind direction shifted notably to southerly (S: 44.4%, Fig.S9c), corresponding on a  
410 larger scale to the marine/coastal air mass trajectory CL1 (22.22%, Fig.S8c). CL1 served as the most  
411 important transport pathway for  $\text{NH}_3$  in the fall, with an average concentration as high as 3.13  $\mu\text{g}\cdot\text{m}^{-3}$   
412 (Table S4), substantially higher than that of continental pathways. After 4 h, as  $\text{O}_3$  gradually decreased  
413 and primary emissions increased, pollutant accumulation occurred, and BC and POC rebounded (Fig.  
414 S12c). The contribution of primary emissions (e.g., BC, POC) to aerosols was significantly enhanced,  
415 and overall  $\kappa_{\text{inorg}}$  (0.55) was low.

416 Winter NPF events were also preceded by an accumulation of gaseous precursors (Fig. 5d). However,  
417 elevated emissions from sources such as heating led to high BC and POC during the initial NPF stage  
418 (1.86 and 1.02  $\mu\text{g}\cdot\text{m}^{-3}$  at -4 h, Fig. S12d). These abundant primary particles strongly suppressed new  
419 particle formation via intense coagulation scavenging, resulting in persistently low formation rates (FR  
420  $\leq 0.47 \text{ cm}^{-3}\cdot\text{s}^{-1}$ ). Photochemical activity was limited under low winter temperatures (Fig. S11d). As  
421 temperatures continued to drop later in the event (after 6 h), condensation-driven conversion of gaseous  
422 precursors to particles increased (Jokinen et al., 2018). During the 6–10 h period, the high concentrations  
423 of precursors reached supersaturation under the low-temperature conditions, promoting the rapid  
424 formation of particulate ammonium nitrate (nitrate concentration increased from 4.21 to 5.14  $\mu\text{g}\cdot\text{m}^{-3}$ ,  
425 Fig. 6d). In winter, the air masses were mainly dominated by the northwesterly continental air mass  
426 originating from Siberia (CL1, Fig.S8d). Particles within this air mass exhibited relatively high  $\kappa_{\text{inorg}}$   
427 (0.59, Table S3), and the introduction of these hygroscopic components effectively offset the dilution of

428 overall hygroscopicity caused by BC and POC. During the 8–10 h period, northwesterly winds persisted,  
 429 and their frequency gradually increased, which also explains the gradual increase in  $\kappa_{inorg}$  values (from  
 430 0.57 to 0.61, Fig.S10).  
 431 In summary, in spring, high  $\text{NH}_3$  and photochemistry drive strong nucleation, but high CS and secondary  
 432 inorganic salts suppress growth. Summer marine air masses provide low CS and high hygroscopicity  
 433 ( $\kappa_{inorg} > 0.6$ ), favoring efficient growth, while fall and winter continental emissions (BC, POC) lower  
 434  $\kappa_{inorg}$  ( $< 0.55$ ) and limit NPF intensity.

435 **3.4 Attribution analysis of particle formation and growth**



436  
 437 **Fig. 7 Non-linear response relationships and interaction analysis between core environmental factors and FR.**  
 438 **Node size and inner numbers denote feature importance (mean |SHAP|). Node color indicates contribution**  
 439 **direction (green: positive; pink: negative). Edge width reflects interaction strength; edge color indicates**  
 440 **interaction direction (purple: synergistic; orange: antagonistic).**

441 According to SHAP analysis (Fig.S14), the main contributors to FR in Fuzhou are nucleation mode  
 442 (76.2%), CS (13.8%),  $\text{NH}_3$  (1.3%), and  $\text{SO}_2$  (0.6%). Physical processes explain ~90% of the variance. A  
 443 prominent feature is the sharp  $\text{NH}_3$  threshold at  $4 \mu\text{g}\cdot\text{m}^{-3}$ : below this,  $\text{SHAP} \approx -0.025$ ; above, it turns  
 444 positive and rises by 0.2 at  $10 \mu\text{g}\cdot\text{m}^{-3}$ . CS shows a clear inhibition onset at  $0.03 \text{ s}^{-1}$ , with SHAP dropping  
 445 from 0 to -0.5 as CS increases to  $0.08 \text{ s}^{-1}$ . Temperature has a positive SHAP only within 20–25°C (peak  
 446 ~0.01), decreasing by 40% at 35°C. As shown in Fig. 7, the strongest interaction is between nucleation

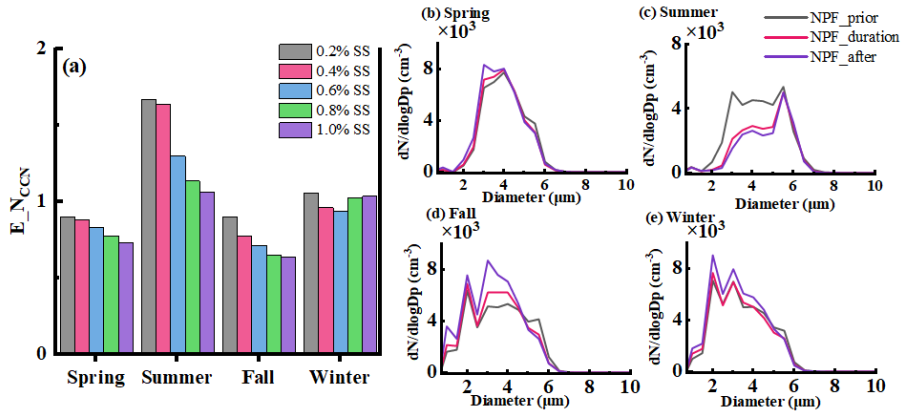
447 mode and CS (0.40), far exceeding other pairs (NH<sub>3</sub>-nucleation mode: 0.04), highlighting that the net FR  
448 is governed by the competition between particle formation and scavenging.

449 For the Aitken mode, the driving forces shift notably. CS remains the top contributor, followed by  
450 accumulation mode (13.8%) and nucleation mode (7.1%). As shown in Fig.S15, a key distinction from  
451 FR is the temperature response. Instead of a bell shape, SHAP increases linearly from 0 to 0.1 over 20–  
452 35°C, indicating that high temperatures accelerate particle growth, enabling a rapid transition from  
453 nucleation to the Aitken mode. The NH<sub>3</sub> threshold at 4 µg·m<sup>-3</sup> persists, showing its continued role in  
454 particle growth. RH exerts a linear negative effect, turning SHAP negative above 60%, suggesting  
455 hygroscopic growth or coagulation loss. In Fig.S16, the CS-nucleation mode interaction strength is 0.12,  
456 lower than in FR but still dominant, implying that strong nucleation can offset high CS losses.

457 In summary, the SHAP attribution reveals two distinct regimes. FR is dominated by CS, accompanied  
458 by a sharp chemical trigger (NH<sub>3</sub> > 4 µg·m<sup>-3</sup>) and a narrow temperature window (20–25°C). The Aitken  
459 mode, while still influenced by CS, is primarily driven by temperature-accelerated growth (linearly  
460 increasing above 20°C). Ammonia acts as a persistent enhancer in both stages, whereas high RH (>60%)  
461 consistently suppresses Aitken mode concentrations.

### 462 **3.5 Particle growth controls CCN formation from NPF events**

463 In summer, although NPF frequency was the lowest, it had a significant enhancing effect on N<sub>CCN</sub>.  
464 E<sub>N<sub>CCN</sub></sub> at 0.4 % SS was as high as 1.64 (Fig. 8a). In the initial stage of NPF events (0–2 hours), N<sub>CCN</sub>  
465 showed a sharp decline. At 0.4 % SS, it decreased from about 2078 cm<sup>-3</sup> to 1187 cm<sup>-3</sup> (Fig. S17b).  
466 However, after 2 h, N<sub>CCN</sub> recovered noticeably and later returned to or even exceeded initial levels. The  
467 CCN size distribution (Fig. 8c) showed that during the event, smaller CCN (1–3 µm) decreased, while  
468 CCN of 5.5–6.5 µm increased. For instance, CCN at 6 µm increased from 2607.7 to 3147.8 cm<sup>-3</sup>. Summer  
469 NPF promoted CCN growth to larger sizes. However, the daily average N<sub>CCN</sub> on summer NPF days was  
470 lower than on non-NPF days, possibly due to the extremely low NPF frequency (4.35 %) and the sharp  
471 decline in CCN at the beginning of events, affecting the daily average.



472

473 **Fig.8** The contribution of NPF events to cloud condensation nuclei (CCN) across seasons: (a) CCN  
 474 enhancement ( $E_{N_{CCN}}$ ), and (b-e) particle number size distributions at 2 hours before, during, and 5 hours  
 475 after the NPF event for seasons.

476 Spring NPF events' impact on  $N_{CCN}$  showed significant suppression. Throughout the event,  $N_{CCN}$  at  
 477 various supersaturation levels showed only weak and slow increases.  $N_{CCN}$  (0.4 % SS, the same as below)  
 478 increased from a pre-event average ( -4 to -1 h) of about  $2636 \text{ cm}^{-3}$  to  $3192 \text{ cm}^{-3}$  at 4 h, then decreased  
 479 slowly from 4 to 6 h, with a larger decline at higher supersaturations (Fig. S17a).  $E_{N_{CCN}}$  at 0.4 % SS  
 480 was only 0.88. This phenomenon corresponds to the "high formation, suppressed growth" characteristic  
 481 of spring NPF. Despite the explosive generation of nucleation-mode particles, severe competition under  
 482 high CS severely hindered subsequent growth of new particles, preventing them from effectively growing  
 483 to CCN activation sizes, resulting in a weak or even negative contribution to CCN.

484 In fall events, from 2 h onward,  $N_{CCN}$  began to increase, rising from  $3471 \text{ cm}^{-3}$  to a maximum of  $4752$   
 485  $\text{cm}^{-3}$ , forming a high-value plateau lasting from 3\_ to 8 h (Fig. S17d). After the NPF event,  $N_{CCN}$  increased  
 486 significantly across the 1-5  $\mu\text{m}$  size range (Fig. 8d). Fall NPF events most effectively and broadly  
 487 increased the number of particles available for cloud droplet activation in the atmosphere. Although  
 488  $E_{N_{CCN}}$  was lower due to the modest initial stage, the post-event enhancement effect was significant.  
 489 This evolution process is consistent with the sustained particle growth process in fall NPF, allowing new  
 490 particles to grow steadily to CCN activation sizes.

491 In winter NPF events,  $N_{CCN}$  was low in the early stage (0–4 h), with insignificant growth. However, from  
 492 5 h onward,  $N_{CCN}$  growth became significant, increasing from  $4483 \text{ cm}^{-3}$  to  $6173 \text{ cm}^{-3}$  and remaining  
 493 stable at high levels (Fig. S17d). During the event, changes in the CCN size distribution were not obvious.

494 However, after the NPF event, CCN in the 2–5  $\mu\text{m}$  size range showed the most significant growth (e.g.,  
495 at 2  $\mu\text{m}$ , from 7073.0 to 9045.1  $\text{cm}^{-3}$ ; Fig. 8e).

#### 496 **4 Conclusions**

497 This year-long observational study in coastal Fuzhou revealed distinct seasonal patterns in new particle  
498 formation (NPF) and its impact on cloud condensation nuclei (CCN). We identified 46 NPF events,  
499 which predominantly occurred between 09:00 and 12:00. Key quantitative results include: the highest  
500 seasonal formation rate (FR) in spring ( $5.56 \text{ cm}^{-3} \text{ s}^{-1}$ ), the highest growth rate (GR) in summer (peak at  
501  $11.68 \text{ nm h}^{-1}$ ), and the strongest CCN enhancement in summer ( $E_{\text{NCCN}} = 1.64$  at 0.4 % SS). In fall and  
502 winter, CCN increases (13–65 %) lag NPF events by 3–5 h.

503 A total of 46 NPF events occurred during the observation period, with a frequency of 12.7 %. NPF event  
504 start times were mainly concentrated between 08:00 and 13:00 (accounting for 85 % of all events), with  
505 an average duration of 4 h. The annual averages for formation rate (FR), growth rate (GR), condensation  
506 sink (CS), coagulation sink (CoagS), and condensable vapor concentration (C) were  $3.94 \pm 8.26 \text{ cm}^{-3} \cdot \text{s}^{-1}$ ,  
507  $5.20 \pm 1.78 \text{ nm} \cdot \text{h}^{-1}$ ,  $4.2 \times 10^{-2} \text{ s}^{-1}$ ,  $5.6 \times 10^{-4} \text{ s}^{-1}$ , and  $16.7 \times 10^7 \text{ cm}^{-3}$ , respectively.

508 The seasonal contrast is mechanistically driven by the interplay between precursor availability, CS, and  
509 aerosol chemistry. Spring conditions favor high FR due to strong photochemistry and abundant  
510 precursors, but high CS suppresses subsequent growth. In summer, the occurrence of NPF events is often  
511 accompanied by a transition in sea-land breeze circulation. The northerly land breeze shifts to  
512 northeasterly/easterly sea breezes, effectively transporting clean marine air masses to the observation site.  
513 This reduces the CS to its seasonal minimum ( $1.08 \pm 0.31 \times 10^{-2} \text{ s}^{-1}$ ), favoring efficient particle growth and  
514 thereby sustaining the highest growth rate (GR) observed across all seasons. The chemical composition  
515 shifts from being dominated by sulfate and sea salt with high hygroscopicity in summer ( $\kappa_{\text{inorg}} > 0.6$ ) to  
516 low hygroscopicity in fall ( $\kappa_{\text{inorg}} = 0.55$ ), directly modulating particle hygroscopicity and cloud  
517 condensation nuclei (CCN) activation potential.  
518 Using XGBoost-SHAP, FR is dominated by nucleation mode (76.2 %) and CS (13.8 %).  $\text{NH}_3 > 4 \mu\text{g} \cdot \text{m}^{-3}$   
519 enhances FR,  $\text{CS} > 0.03 \text{ s}^{-1}$  inhibits FR (SHAP drops to  $-0.5$  at  $0.08 \text{ s}^{-1}$ ), and Temperature benefits FR  
520 only within 20–25 °C. For Aitken mode, temperature linearly promotes growth above 20°C, while

521 [RH > 60 % suppresses it. The strong nucleation-CS interaction \(0.40\) highlights the competition between](#)  
522 [formation and scavenging.](#)

523 This work demonstrates that the climatic impact of NPF in coastal urban areas is not simply a function  
524 of its occurrence frequency or formation strength. Instead, it is seasonally modulated by a competition  
525 between formation and growth-sink processes, and by the resulting aerosol chemical composition. The  
526 decoupling of high FR from effective CCN production (as in spring) implies that climate models using  
527 NPF frequency as a proxy for aerosol indirect effects may overestimate the impact in high-CS coastal  
528 regions. Conversely, the efficient growth and CCN enhancement in summer suggest that even infrequent  
529 NPF events can substantially influence cloud properties in such environments. These insights are crucial  
530 for developing more accurate parameterizations of aerosol-cloud-climate interactions in rapidly  
531 developing coastal zones.

#### 532 **Data availability**

533 Data will be made available on request.

#### 534 **Author contributions**

535 Conceptualization was completed by ZW and HW. Formal analysis and software modification were  
536 carried out by ZW and HW. The initial draft was written by ZW, incorporating tables provided by HW.  
537 The first draft was revised by ZW, HW, and YB, with input from HW, YB, FZ, WL, JH, LS, and ZX;  
538 subsequent versions of the manuscript were reviewed and edited by all authors. Data curation and  
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#### 540 **Competing interests**

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

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