

Critical Role of Dust Induced Electrostatic Coagulation in the Evolution of Aerosol Size Distributions in the Atmosphere

Luoqiu Quan¹, Ruoyu Zhang¹, Gui Dai¹, Xinghua Jiang¹, Xiangyang Wang¹, Xiewen Ma¹, Xinyu Liu¹, Qianqian Gao¹, Xiaohui Lu^{1*}, Xiaofei Wang^{1,2,3*}

¹Department of Environmental Science and Engineering, Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention, Fudan University, Shanghai 200433, China.

²Shanghai Institute of Pollution Control and Ecological Security, Shanghai 200092, China.

³Fudan Zhangjiang Institute, Shanghai 201203, China.

Correspondence to:

Xiaofei Wang (xiaofeiwang@fudan.edu.cn)

Xiaohui Lu (luxiaohui@fudan.edu.cn)

Abstract. Coagulation modifies the particle size distributions (PSD) of atmospheric aerosols, affecting their optical properties, cloud droplet activation, and gravitational deposition. While Coulomb forces may impact coagulation processes between charged aerosols, such as dust, most coagulation models neglect the effects of aerosol charge. Here, we address the lack of single-particle charge measurements for dust aerosols by developing a method to retrieve their joint size-charge distributions. By incorporating aerosol charge into the coagulation kernel, simulations in a dust-only scenario at typical environmental concentrations show that, on hourly timescales, electrostatic force leads to a reduction of up to ~64% in number concentration relative to Brownian coagulation. Moreover, electrostatic coagulation between dust and ambient sub-500 nm aerosols modifies the latter's PSD by ~10% compared with Brownian coagulation. These results strongly suggest that electrostatic coagulation should be considered in air quality models.

1 Introduction

Changes in the aerosol particle size distribution (PSD) alter aerosol optical properties and deposition behavior. These changes affect atmospheric radiation, cloud droplet activation, and aerosol removal processes (Tegen et al., 1996; Pöschl, 2005). One important driver of PSD evolution is coagulation. Coagulation shifts aerosols toward larger sizes and reduces the total number concentration. Quantifying PSD evolution due to coagulation is essential for assessing atmospheric effects. Aerosol coagulation can be driven by Brownian motion, van der Waals and Coulomb interactions, and hydrodynamic (shear/turbulence-induced) processes. Different mechanisms lead to different coagulation kernels and thus distinct PSD evolution (Seinfeld et al., 2016).

Most widely used coagulation models use Brownian coagulation as the fundamental mechanism and include no explicit charge terms in the coagulation kernel (Lee et al., 2009; Ramnarine et al., 2019; Grell et al., 2005). When aerosols carry charge, Coulomb forces alter aerosol collision and coalescence processes. Oppositely

34 charged aerosols experience Coulomb attraction and collide more frequently, whereas like-charged aerosols
35 experience Coulomb repulsion and collide less often (Harrison and Carslaw, 2003). Experimental and
36 numerical studies show that when aerosols carry large opposite charges or the charge distribution is highly
37 asymmetric, the electrostatic coagulation rate is significantly higher than the Brownian coagulation rate
38 (Adachi et al., 1981). Therefore, using such Brownian models to assess the coagulation of highly charged
39 atmospheric aerosols may introduce bias for charged aerosols. Explicit consideration of Coulomb interactions
40 in the coagulation process is necessary to improve the accuracy of modeled PSD evolution.

41 Highly charged aerosols are common in the atmosphere, typically including dust aerosols, volcanic ash, sea
42 spray, and urban coarse aerosols (Harrison and Carslaw, 2003; Cimorelli and Genareau, 2022). Dust aerosols
43 with geometric diameters up to 20 μm have an emission of approximately 5000 Tg yr^{-1} and possess long-
44 range transport capability (Kok et al., 2021). These features produce significant environmental effects by
45 influencing atmospheric radiative forcing and cloud condensation nuclei (CCN) number concentration.
46 Meanwhile, the PSD of dust aerosols strongly influences their radiative properties, CCN concentration, and
47 deposition rate (Tegen et al., 1996; Lee et al., 2009). Thus, dust aerosols are a highly representative system
48 for investigating coagulation processes in highly charged aerosol populations. Quantifying the evolution of
49 the PSD of dust aerosols during coagulation is essential for improving such assessments. Based on physics-
50 based numerical calculations, Mallios et al. (2022) predicted mean net dust aerosol charges of approximately
51 0.5 – 2000 e, exceeding those expected under Boltzmann equilibrium. The existence of such charge states
52 suggests that electrostatic interactions may become non-negligible, highlighting the potential importance of
53 electrostatic coagulation in dust aerosol systems (Adachi et al., 1981). The specific differences between
54 electrostatic and Brownian coagulation of dust aerosols in driving the PSD evolution of ambient aerosols in
55 dust-laden environments are not yet well understood.

56 Techniques for measuring single-particle charges on dust aerosols are required to quantify PSD evolution
57 driven by electrostatic coagulation. Such techniques must provide polarity discrimination and size-resolved
58 precision. Existing approaches can be broadly classified into three categories: bulk net-charge measurements
59 (e.g., Faraday-cup or induction electrometry), single-particle trajectory or deflection measurements, and
60 high-precision single-particle instruments based on levitation or trapping (e.g., electrodynamic balance;
61 Zhang et al., 2020; Li et al., 2022). These methods usually deliver only some of the above capabilities—
62 rarely all at once, especially in high-throughput, in situ settings. Obtaining single-particle charge
63 measurements for dust aerosols that are directly applicable to electrostatic coagulation modeling remains a
64 major technical challenge.

65 The core objective of this study is to quantify the differences between electrostatic and Brownian coagulation
66 of dust aerosols in driving the PSD evolution of ambient aerosols during dust events. To address this objective,
67 we develop a new method to obtain single-particle charge values of dust aerosols that can be directly used
68 for electrostatic coagulation modeling by means of laboratory measurements and computational inversion.
69 The measured charges serve as initial conditions for subsequent coagulation simulations, and the method
70 provides a reusable workflow for related research. Based on the comparative simulation results, the role of
71 explicit charge inclusion in coagulation modeling is evaluated.

72 **2 Materials and Methods**

73 This section describes the measurements, data processing, and coagulation model. The PSDs and electrical
74 mobility diameter distributions of laboratory-generated dust aerosols were obtained from measurements,
75 while single-particle charge distributions were derived from measurements and computational inversion. The
76 PSDs of ambient sub-500 nm aerosols were obtained from field measurements, and their charge distributions
77 were obtained through computation. The number concentrations of dust aerosols, with or without ambient
78 sub-500 nm aerosols, were mapped onto a common size-charge matrix and used as model initial conditions.
79 The model simulated Brownian and electrostatic coagulation and updated the aerosol number concentration
80 matrix over time.

81 **2.1 Laboratory Dust Aerosol Generation**

82 **2.1.1 Soil Samples**

83 This study used eight soil samples to produce laboratory-generated dust aerosols. Two were collected from
84 the Dunhuang dust source area, Gansu Province, China (S1, S2). Three were collected from the Inner
85 Mongolia dust source area (Ulanqab and Hohhot), China (S3–S5). Three were collected from non-dust-source
86 areas in Qingxi Country Park, Shanghai (S6), Fudan University’s Jiangwan Campus, Shanghai (S7), and
87 Baoshi Town in Anju District, Suining, Sichuan Province (S8). All samples were passed through a 100 mesh
88 nylon sieve to remove coarse particles and organic debris. Site coordinates and soil texture are listed in Table
89 S1.

90 **2.1.2 Dust Aerosol Generator**

91 A dust aerosol generator (SyGAVib) was used to produce laboratory-generated dust aerosols (Qu et al., 2020).
92 The device consists of a cylindrical acrylic chamber, a loudspeaker, and an aluminum cup with an open top.
93 Operating parameters were set following Qu et al. (2020) to generate a stable dust plume. Each experiment
94 used 0.3 g of soil placed in the aluminum cup, with the cup fixed to the loudspeaker diaphragm. The
95 loudspeaker was driven at 100 Hz with medium output power to loosen particles via collisions. Three bottom

96 inlet ports supplied dried and filtered air at a total flow rate of 8 liters per minute (LPM). The two lower side
97 ports each supplied 3.5 LPM of sheath air to provide upward momentum, and the port above the cup delivered
98 air of 1 LPM into the cup to simulate turbulence and loft the dust aerosols. To avoid the effect of humidity
99 on Coulomb forces between aerosols (Ma et al., 2023), the plume relative humidity was maintained at 25–
100 35%. A temperature-humidity probe was placed at the top of the chamber. The setup is shown in Figure S1.
101 It should be noted that these aerosols are more representative of freshly generated dust aerosols under near-
102 source conditions than of aged atmospheric dust after long-range transport.

103 2.2 Dust Aerosol Measurements

104 2.2.1 Size and Electrical Mobility Distributions

105 Size distributions of dust aerosols were measured with an Aerodynamic Particle Sizer (APS, TSI Inc. Inlet
106 flow rate: 1 LPM) over 0.5–20 μm , whereas aerosols $< 0.5 \mu\text{m}$ were measured with a Scanning Mobility
107 Particle Sizer (SMPS, TSI Inc. Sampling flow rate: 0.3 LPM). For consistency, all aerosol sizes were
108 converted to electrical mobility diameter, which more accurately approximates the geometric diameter of
109 non-spherical aerosols. The detailed conversion formula is provided in Eq. (3). Electrical mobility
110 distributions were measured with an SMPS without a neutralizer, covering $1.56 \times 10^{-9} - 1.07 \times 10^{-6} \text{ m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$.
111 The schematic is in Figure S1.

112 2.2.2 Single-Particle Charge Measurement

113 The experimental setup is shown in Figure 1. The laboratory-generated dust aerosols were then directed into
114 the Differential Mobility Analyzer (DMA, Models 3080 and 3082, TSI Inc., inlet flow rate: 1 LPM, sheath
115 flow rate: 10 LPM) at prescribed electrical mobilities Z_p (Table S2), and the aerodynamic diameter of the
116 classified aerosols was measured with an APS. The single-particle charge distribution was retrieved through
117 joint analysis of the set electrical mobility and the electrical mobility diameter (D_p).

118 Electrical mobility equation:

$$119 \quad Z_p = \frac{neC}{3\pi\mu D_p} \quad (1)$$

120 Z_p is the electrical mobility ($\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$), n is the single-particle charge, e is the elementary charge (1.6×10^{-19}
121 C), π is the circular constant, and μ is the dynamic viscosity of air ($1.85 \times 10^{-5} \text{ Pa} \cdot \text{s}$ at $25 \text{ }^\circ\text{C}$), D_p is the electrical
122 mobility diameter (m).

123 where C is the Cunningham slip correction factor, calculated as (Seinfeld et al., 2016):

124
$$C = 1 + \frac{2\lambda}{D} [1.257 + 0.4\exp(-\frac{1.1D}{2\lambda})]$$
 (2)

125 D is the aerosol diameter (m), λ is the molecular mean free path (68×10^{-9} m).

126 The aerodynamic diameter was converted to the electrical mobility diameter using the size conversion
127 relationship (Seinfeld et al., 2016):

128
$$D_p = D_a \sqrt{\chi^3 \frac{\rho_0 C(D_m)^2 C(D_a)}{\rho_p C(D_{ve})^3}}$$
 (3)

129 is derived from the following two equations:

130
$$\frac{D_p}{C(D_p)} = \frac{D_{ve}\chi}{C(D_{ve})}$$
 (4)

131
$$D_a = D_{ve} \sqrt{\frac{\rho_p C(D_{ve})}{\chi \rho_0 C(D_a)}}$$
 (5)

132 χ is the dynamic shape factor under the experimental conditions (set to 1.0 assuming spherical dust aerosols),
133 D_a is the aerodynamic diameter (m), D_{ve} is the volume equivalent diameter (m), ρ_0 is the reference density
134 (1 g/cm^3), and ρ_p is the density of dust aerosol particles, taken as 2.65 g/cm^3 (Haywood et al., 2003a). Missing
135 charge bin concentrations were obtained by linear interpolation along the charge axis.

136 Under each prescribed electrical mobility condition Z_p , the APS provided the PSD ($dN/d\log D_p$) of the DMA-
137 classified dust aerosols for different aerodynamic diameter bins. The aerodynamic diameter D_a measured by
138 the APS was converted to the electrical mobility diameter D_p using Eq. (3). For each logarithmic particle-
139 diameter bin ($\log D_p \text{ bin}$), the corresponding number of charges per particle n was then calculated from
140 Eq. (1) using the prescribed Z_p and the converted D_p . Therefore, each prescribed electrical mobility condition
141 produced one aerosol number concentration line in the two-dimensional size-charge space.

142 For simplicity, the concentration was not jointly normalized over the particle-size and charge dimensions. It
143 was expressed as $dN/d\log D_p$, rather than as a combined two-dimensional concentration form such as
144 $dN/(d\log D_p dn)$ or $dN/(d\log D_p d\log n)$. Each $dN/d\log D_p$ value was assigned to the corresponding calculated
145 charge number n . The full two-dimensional size-charge distribution was reconstructed from multiple

146 measured lines obtained under different prescribed electrical mobility conditions, and the bins not directly
147 covered by these measured lines were filled by linear interpolation between adjacent lines.

148 The interpolation uncertainty is mainly associated with the high-charge tail, where aerosol number
149 concentrations are inherently low and therefore more sensitive to data-processing methods. However, the
150 prescribed electrical mobility range in this study is relatively broad and still includes measured points in the
151 high-charge tail. Therefore, the uncertainty associated with the high-charge tail is expected to have a limited
152 influence on the reconstructed size–charge distribution.

153 It should also be noted that a dynamic shape factor of $\chi = 1$ was assumed in the conversion from aerodynamic
154 diameter to electrical mobility diameter as a simplifying assumption. Since irregular mineral dust aerosols
155 typically have $\chi > 1$, this assumption may shift the particle size range associated with highly charged aerosols,
156 while this assumption affects the converted particle size, but does not change the measured charge
157 characteristics. This uncertainty does not affect the qualitative comparison between the two cases, because
158 both cases start from the same initial PSD and therefore share the same underlying Brownian coagulation
159 pathway, with the only difference being whether electrostatic interactions are include.

160 In addition, the finite DMA mobility selection range may introduce a small bias toward higher inferred charge
161 states for large aerosols. This is because aerosols with large diameters and only a few charges may fall below
162 the lower DMA mobility selection limit and therefore cannot be fully selected. According to the electrical
163 mobility definition equation, the lower DMA mobility selection limit used in this study, $4.68 \times 10^{-9} \text{ m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$,
164 corresponds to a minimum required charge of only ~ 5 e for aerosols with diameters of $\sim 1 \mu\text{m}$, ~ 10 e for
165 $\sim 2 \mu\text{m}$, and ~ 35 e even near the upper end of the measured size range ($\sim 7 \mu\text{m}$). Importantly, $\sim 59\%$ of the
166 total dust aerosol number concentration is distributed within the $1 - 2 \mu\text{m}$ size range, where the lower DMA
167 mobility boundary corresponds to only $\sim 5 - 10$ e. However, the mean charge level of dust aerosols in this
168 dominant $1 - 2 \mu\text{m}$ size range is still on the order of 10^2 e, much higher than the lower-boundary charge
169 values.

170 The number fraction of dust aerosols outside the lower DMA mobility limit was estimated on a particle size
171 bin basis. For each particle size bin, the charge value corresponding to the lower DMA mobility boundary
172 was first calculated based on the electrical mobility definition equation. The number concentration below this
173 boundary was then estimated from the fitted charge distribution for that particle size bin. Specifically, the
174 charge distribution in each particle size bin was empirically fitted using a Gaussian-shaped function in $\ln(n)$
175 space:

176

$$N_{D_p}(n) = A_{D_p} \exp\left[-\frac{(\ln n - \mu_{D_p})^2}{2\sigma_{D_p}^2}\right] \quad (6)$$

177

178

179

180

181

182

where n is the number of charges per particle, D_p is the particle diameter of a given size bin, $N_{D_p}(n)$ is the number concentration at charge state n for particles with diameter D_p , and A_{D_p} , μ_{D_p} , and σ_{D_p} are empirical fitting parameters obtained separately for each particle size bin. Based on this particle size bin based estimation, only ~0.6% of the dust aerosols in this study are estimated to fall below the lower DMA mobility limit. Therefore, under the present operating conditions, the dust aerosols considered in this study would generally remain above the lower DMA mobility selection limit.

183

184

185

186

A custom charged particle remover (CPR) operated at 3.5 kV was used to determine the neutral fraction of dust aerosols (Zhang et al., 2023). The CPR consists of two coaxially aligned stainless-steel tubes that create a radial electric field, which removes charged aerosols and allows only neutral aerosols to pass through unaffected (design and operation details in Figure S2).

187

2.3 Ambient Sub-500 nm Aerosol Size Distribution Measurement and Charge Calculation

188

189

190

191

192

193

194

195

196

197

198

199

The PSD of representative ambient sub-500 nm aerosols was determined from measurements collected during periods without dust events at the seventh floor of the Environmental Science Building, Jiangwan Campus of Fudan University, Shanghai, China, on 30 September 2024. The detailed geographic coordinates of the measurement site are provided in Table 3. Given that ultrafine aerosols (<100 nm) in urban environments typically contribute the majority of the total number concentration (>80%) (Kumar et al., 2014; Morawska et al., 2008), and that the WMO Global Atmosphere Watch (GAW) multi-site analysis also used the 10 – 500 nm size range to represent total number concentration (Rose et al., 2021), the electrical mobility diameter distribution of ambient sub-500 nm aerosols was measured with an SMPS over 14 – 500 nm. The measurement setup is shown in Figure S4. Assuming a natural bipolar ion background (Tigges et al., 2015), aerosol charge states were assumed near Boltzmann equilibrium. The charge distribution for each size bin was computed from the measured size distribution using the Boltzmann formulation (Liu and Pui, 1974; Table S4).

200

2.4 Coagulation Modeling

201

2.4.1 Input Matrix Construction

202

203

In the coagulation model, aerosol number concentrations are represented on a unified matrix in size and charge. Dust aerosol model inputs were derived from three Inner Mongolia soil samples. Given that Mongolia

204 accounted for more than 42% of dust concentrations in northern China during March–April 2023 (Chen et
 205 al., 2023) and shares a dust source belt and similar emission and transport pathways with Inner Mongolia
 206 (Mu and Fiedler, 2025), dust aerosols generated from Inner Mongolia soils are representative. The dataset
 207 was discretized on a two-dimensional size-charge matrix, defined by electrical mobility diameter D_p (Table
 208 S5) and single-particle charge number $z \in \{-1000, -999, \dots, 999, 1000\}$. The size matrix comprised 131
 209 logarithmically spaced bins from 14.1 nm to 7 μm . This yielded three number concentration matrices $N_k(D_p,$
 210 $z)$ for $k = 1, 2, 3$. Each N_k was normalized to a joint probability density matrix:

$$211 \quad f_k(D_p, z) = \frac{N_k(D_p, z)}{\sum_{D_p, z} N_k(D_p, z)} \quad (7)$$

212 and the representative joint probability density function was obtained by taking the element-wise arithmetic
 213 mean:

$$214 \quad \bar{f}(D_p, z) = \frac{1}{3} \sum_{k=1}^3 f_k(D_p, z) \quad (8)$$

215 Following Chen et al. (2023), the dust aerosol number concentration of $\sim 300 \text{ \#/cm}^3$ ($\sim 3 \text{ mg/m}^3$) observed in
 216 Beijing during transport from Mongolia was mapped onto the matrix according to the above representative
 217 joint probability density matrix, yielding a representative number concentration matrix of dust aerosols. This
 218 matrix was combined with the ambient sub-500 nm aerosol matrix, or used alone, to form the initial mixed
 219 field that served as the model input. For sensitivity analysis under dust-only conditions, additional
 220 simulations were performed with initial dust aerosol number concentrations of 50, 100, 200, 300, 500, and
 221 1000 \#/cm^3 (Figure 4). This range of concentrations was used to evaluate model stability under varying initial
 222 conditions and to examine the concentration dependence of electrostatic coagulation.

223 **2.4.2 Brownian Coagulation**

224 Under Brownian coagulation, the generation and loss terms are computed on the size matrix for each size bin,
 225 following Zebel (1958) and Oron and Seinfeld (1989a):

$$226 \quad \frac{dN(D_p)}{dt} = \frac{1}{2} \sum_{D'_p} \sum_{D''_p} \beta_{B(D'_p, D''_p)} N(D'_p) N(D''_p) - N(D_p) \sum_{D_p^*} \beta_{B(D_p, D_p^*)} N(D_p^*) \quad (9)$$

227 N is the aerosol number concentration in a size bin ($\#/cm^3$), D_p' and D_p'' are the aerosol diameters (m), D_p^*
 228 denotes the representative size of aerosols colliding with D_p (m), and β_B is the Brownian coagulation kernel
 229 (m^3/s), calculated using the Fuchs (1964) formulation at 25 °C.

230 The Brownian coagulation kernel is given by:

$$231 \quad \beta_B = 2\pi(d_1 + d_2)(D_{p1} + D_{p2}) \times \left(\frac{D_{p1} + D_{p2}}{D_{p1} + D_{p2} + 2(\delta_1^2 + \delta_2^2)^{1/2}} + \frac{8(D_1 + D_2)}{(\bar{c}_1^2 + \bar{c}_2^2)^{1/2}(D_{p1} + D_{p2})} \right)^{-1} \quad (10)$$

232 where:

$$233 \quad \bar{c}_i = \left(\frac{8kT}{\pi m_i} \right)^{1/2} \quad (11)$$

$$234 \quad \lambda_i = \frac{8D_i}{\pi \bar{c}_i} \quad (12)$$

$$235 \quad \delta_i = \frac{1}{3D_{pi}\lambda_i} [(D_{pi} + \lambda_i)^3 - (D_{pi}^2 + \lambda_i^2)^{3/2}] - D_{pi} \quad (13)$$

$$236 \quad d_i = \frac{kTC_c}{3\pi\mu D_{pi}} \quad (14)$$

237 D_{pi} is the aerosol diameter (m), k is the Boltzmann constant ($1.380649 \times 10^{-23} \text{ J}\cdot\text{K}^{-1}$), T is the temperature
 238 (298.15 K), and m_i is the aerosol mass (kg).

239 Coagulation satisfies volume conservation:

$$240 \quad D_p = (D_p^3 + D_p^{*3})^{1/3} \quad (15)$$

241 At each time step a pairwise collision rate matrix is formed. Columns correspond to the size bins being
 242 depleted and rows correspond to the pairing size bins that collide with them. The total coagulation rate for a
 243 given size bin is obtained by summing all elements in its column. The remaining number concentration in
 244 the size bin D_p after one time step is:

$$245 \quad N_{rem}(D_p) = N(D_p) - \Delta t N(D_p) \sum_{D_p^*} \beta_B(D_p, D_p^*) N(D_p^*) \quad (16)$$

246 The time step Δt was 1 s for 0–100 s, 10 s for 100–1000 s, and 100 s for 1000–10000 s.

247 For the formation term, the upper-triangular part of the rate matrix was used to avoid double counting. For
 248 each pair in the upper triangle of the pairwise collision rate matrix, the equivalent product size was computed
 249 from volume conservation and mapped to the nearest discrete size bin. The number of newly formed aerosols
 250 was then added to the corresponding product bin. After traversing the upper triangle, the formation term for
 251 each size bin was obtained. The field $N(D_p)$ was updated by adding the formation matrix to the remaining
 252 concentration matrix.

253 2.4.3 Electrostatic Coagulation

254 Electrostatic coagulation was modeled using the Brownian framework with a Coulomb correction applied to
 255 the coagulation kernel:

$$\begin{aligned}
 \frac{dN(D_p, z)}{dt} = & \frac{1}{2} \sum_{D'_p} \sum_{D''_p} \sum_{z'=-1000}^z \beta_{E(D'_p, z-z'), (D''_p, z')} N(D'_p, z-z') N(D''_p, z') \\
 & - N(D_p, z) \sum_{D_p^*} \sum_{z^*} \beta_{E(D_p, z), (D_p^*, z^*)} N(D_p^*, z^*)
 \end{aligned} \tag{17}$$

257 β_E is the electrostatic coagulation kernel (m³/s), derived from the Brownian kernel with a Coulomb
 258 interaction correction. In this study, all parameters were set to 25 °C. z' denotes particles with charge
 259 number smaller than z , and z^* denotes the representative charge of aerosols colliding with z .

260 The electrostatic coagulation kernel is given by (Brownian kernel with Coulomb correction):

$$\beta_E = \frac{\beta_B}{W_c} \tag{18}$$

$$W_c = \frac{e^\kappa - 1}{\kappa} \tag{19}$$

$$\kappa = \frac{z_1 z_2 e^2}{4\pi \epsilon_0 \epsilon (R_{p1} + R_{p2}) kT} \tag{20}$$

264 z_i is the aerosol charge number, e is the elementary charge ($1.60217662 \times 10^{-19}$ C), $\epsilon_0 \epsilon$ is the dielectric
 265 permittivity of air (8.854737×10^{-12} F/m), and R_{pi} is the aerosol effective radius (m).

266 Simulating electrostatic coagulation requires accounting for atmospheric ions. Dust aerosols are typically
 267 transported at altitudes of ~2–5 km, where they are influenced by cosmic-ray ionization (Kok et al., 2021;
 268 Xie et al., 2022). The initial ion number concentration is 440 #/cm³ and the ion production rate is 2 #/cm³·s

269 (Tamm et al., 2006; Israel et al., 1970, 1973; Hoppel et al., 1986a). At each time step, the ion balance and
270 aerosol charging are updated first and coagulation is then applied.

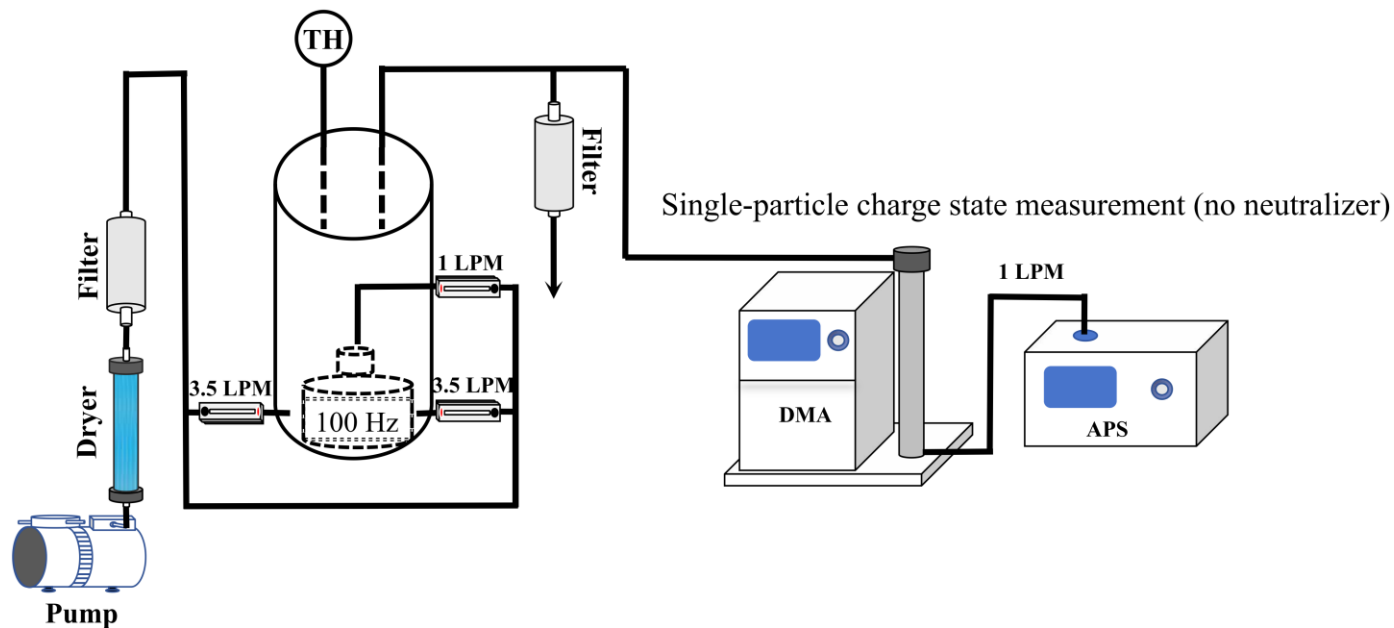
271 The pairwise collision rate matrix in electrostatic coagulation is indexed by paired size and charge (D_p, z).
272 As in Brownian coagulation, the loss for any source cell is obtained by summing the column of the pairwise
273 collision rate matrix corresponding to that cell. The formation term differs in that the product is indexed by
274 both size and charge. The size of newly formed aerosols is computed from volume conservation and mapped
275 to the nearest discrete size bin. The charge of newly formed aerosols is computed from charge conservation
276 and assigned to the corresponding integer charge bin. The resulting size and charge indices are then used to
277 add the newly formed aerosols to the corresponding matrix cell.

278 It should be noted that certain features of the coagulation model may introduce slight biases. The calculation
279 of the size of the product aerosol follows volume conservation and the computed size may deviate from the
280 true volume-equivalent diameter because aerosols are not ideal spheres. Moreover, although a relatively fine
281 size discretization is adopted, binning still introduces errors, which are more apparent when the size
282 difference between dust aerosols and ambient sub-500 nm aerosols is large. Coagulation products are often
283 binned near the size of the larger precursor aerosol. This underestimates the contribution of small aerosols,
284 causes a numerical loss of total aerosol volume, and subtly shifts the PSD toward smaller sizes.

285 **3 Results and Discussion**

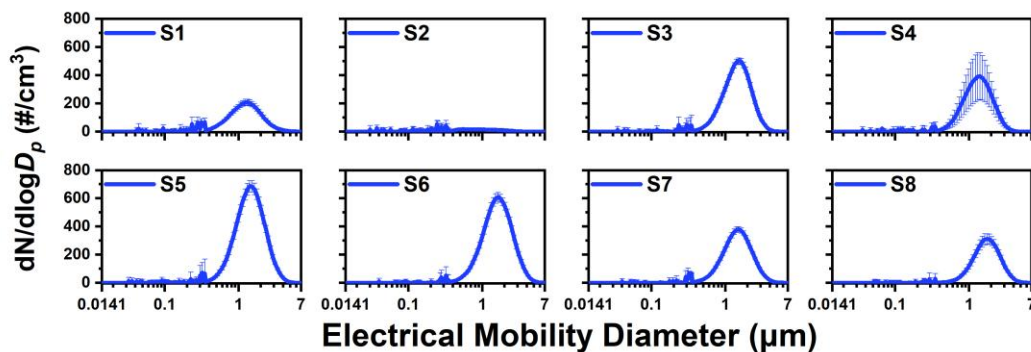
286 **3.1 Size and charge characteristics of laboratory-generated dust aerosols**

287 This study used a DMA – APS measurement system combined with inversion of the electrical mobility
288 equation to obtain size-resolved single-particle charge distributions of individual dust aerosol particles. The
289 experimental setup is shown in Figure 1. These measurements provide the basis for subsequent size – charge
290 coupled analyses and coagulation simulations, and enable a standardized workflow for in situ measurement
291 of charged dust aerosols.



293 **Figure 1.** Schematic of the experimental workflow for measuring single-particle charge.

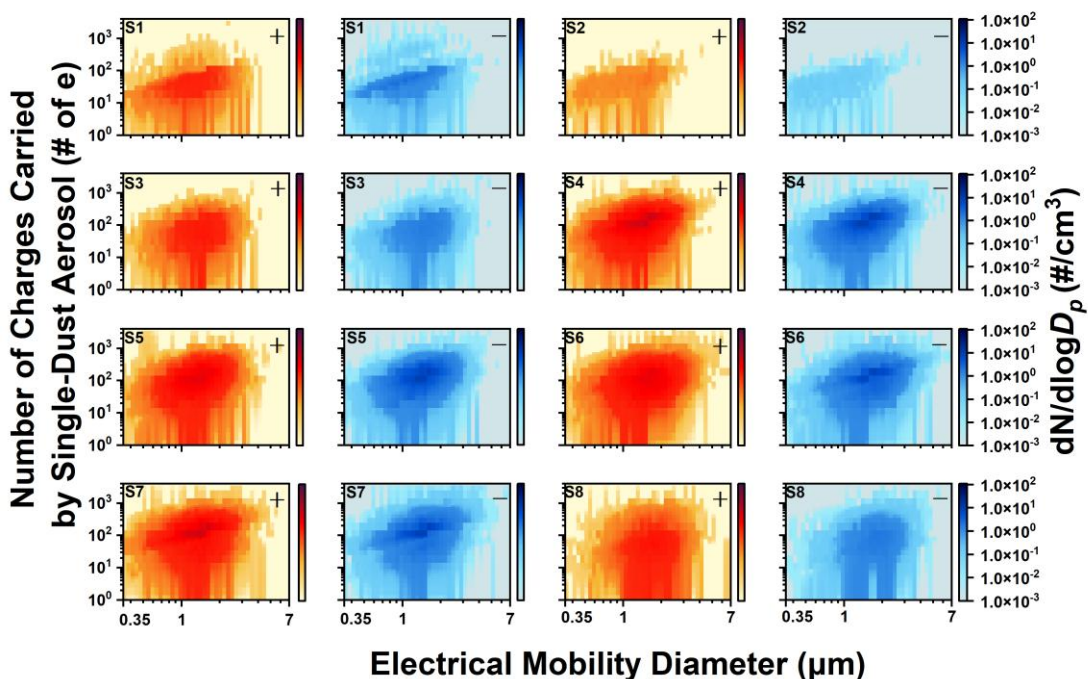
294 The laboratory-generated dust aerosols are shown to be representative of real atmospheric dust (Shao et al.,
 295 2016). Figure 2 shows that the peak diameters of the eight dust aerosol samples fall within 1 – 3 μm ,
 296 consistent with long-range transported atmospheric dust aerosols (Maring et al., 2003). This size distribution
 297 also agrees well with field APS measurements of transported dust in Yinchuan, China, further supporting the
 298 atmospheric representativeness of the laboratory-generated aerosols (Shao and Mao, 2016). Investigating
 299 coagulation within this size range therefore provides greater atmospheric relevance.



301 **Figure 2.** Particle size distributions of dust aerosol samples S1–S8 from 23 nm to 10 μm .

302 The data in Figure 3 indicate that the charge distribution of the laboratory-generated dust aerosols spans a
 303 range of ~ 10 –1000 e , with a peak around 100 e . These values are much higher than those at the bipolar
 304 Boltzmann equilibrium. The distributions are nearly symmetric between positive and negative charges,

305 indicating no pronounced polarity preference. This near-symmetric bipolar character is further supported by
 306 the nearly identical positive and negative electrical mobility distributions in Figure S5. These measurements
 307 directly resolve the size-dependent charge distribution of individual dust aerosols, providing observational
 308 constraints that are typically unavailable in coagulation studies. This nonequilibrium bipolar charge
 309 distribution enhances Coulomb interactions and consequently leads to a higher coagulation rate (Adachi et
 310 al., 1981).



311

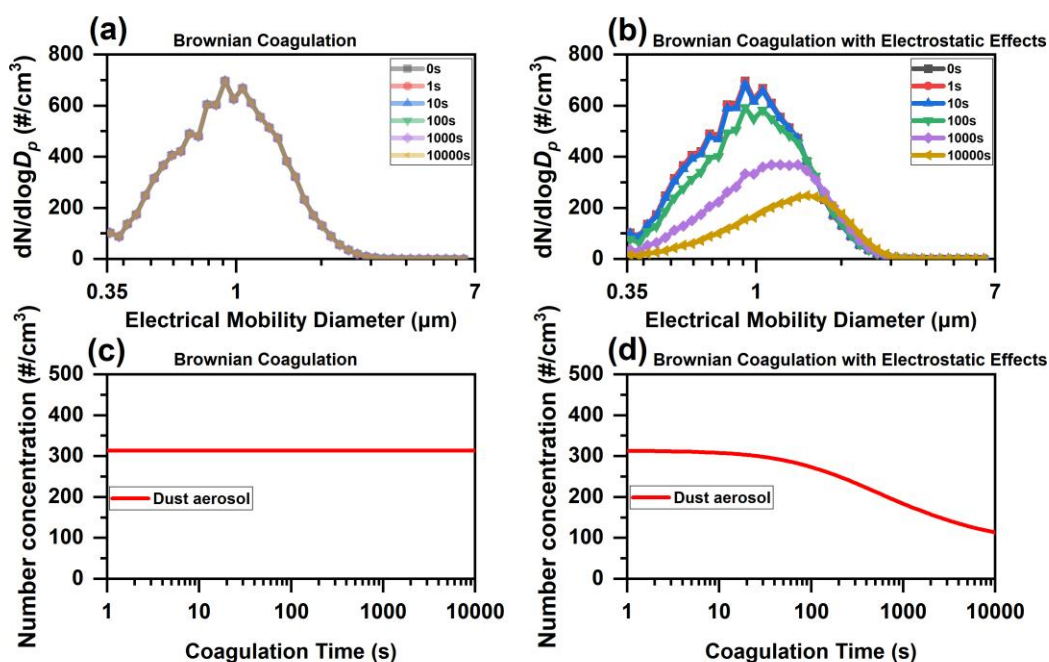
312 **Figure 3.** Maps of the joint distribution of number of charges carried by single-dust aerosol and electrical
 313 mobility diameter for dust aerosol samples S1–S8. The x axis is **electrical mobility diameter** on a logarithmic
 314 scale from 0.7–12.5 μm . The y axis is the number of elementary charges per aerosol on a logarithmic scale
 315 from 1–4000 e. Color encodes number concentration on a logarithmic scale from 10^{-3} – 10^2 $\#/\text{cm}^3$. Red
 316 indicates positively charged aerosols and blue indicates negatively charged aerosols.

317 **3.2 PSD evolution of dust aerosols in dust-only scenario under Brownian and electrostatic coagulation**

318 The PSD evolution under electrostatic coagulation of dust aerosols differs significantly from that under
 319 Brownian coagulation. The size-charge number concentration matrix of dust aerosols was used as the model
 320 input, with an initial total number concentration of $300 \#/\text{cm}^3$. This value was chosen to represent a
 321 characteristic peak in dust number concentrations commonly observed under non-extreme dust conditions in

322 northern China, based on long-term measurements in Beijing and nearby regions (Chen et al., 2023). The
323 choice of dust aerosol number concentration is described in Methods Section 2.4.1.

324 The PSD evolution under Brownian and electrostatic coagulation from 0 to 10000 s was then simulated, as
325 shown in Figure 4. From 0 to 10000 s, the PSD is essentially unchanged under Brownian coagulation (Figure
326 4a), whereas under electrostatic coagulation the peak diameter shifts from ~ 0.9 to $1.5 \mu\text{m}$ and the peak
327 number concentration falls from ~ 700 to 250 \#/cm^3 (Figure 4b). These results show that dust aerosols change
328 the PSD on hourly timescales through electrostatic coagulation. Therefore, calculations of coagulation
329 processes involving highly charged aerosols should explicitly account for the influence of Coulomb forces.

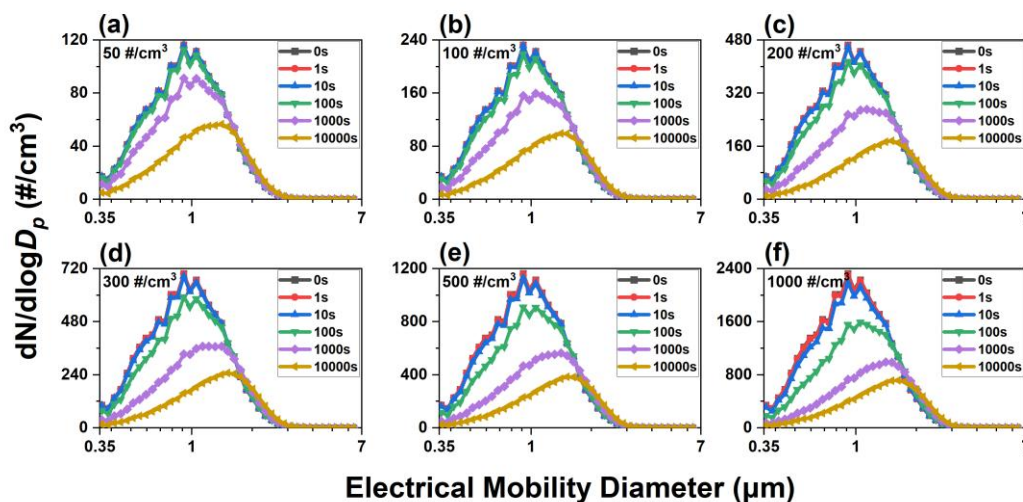


330

331 **Figure 4.** Temporal evolution of the PSD and total number concentration for dust aerosols (dust-only with
332 an initial concentration at 300 \#/cm^3), simulated at $25 \text{ }^\circ\text{C}$. (a) Dust aerosols' PSD under Brownian coagulation,
333 remaining essentially unchanged. (b) Dust aerosols' PSD under electrostatic coagulation. (c) Total aerosol
334 number concentration under Brownian coagulation. (d) Same as (c), but for electrostatic coagulation.

335 In addition, sensitivity tests of dust-only electrostatic coagulation with initial dust aerosol number
336 concentrations from 50 to 1000 \#/cm^3 (Figure 5) show that the qualitative features of PSD evolution remain
337 consistent across this concentration range. The simulations further show that higher initial dust aerosol
338 number concentrations experience a stronger decrease in the PSD peak over 0 – 10000 s. This behavior is
339 consistent with coagulation kinetics, where the collision frequency scales with the square of the number

340 concentration ($dN/dt \propto -KN^2$; Seinfeld et al., 2016). This effect is likely to occur in dense dust plumes or
341 severe dust-storm events in the real atmosphere.



342

343 **Figure 5.** Temporal evolution of the PSD due to electrostatic coagulation under dust-only conditions at
344 different initial number concentrations at 25 °C. (a) 50 #/cm³; (b) 100 #/cm³; (c) 200 #/cm³; (d) 300 #/cm³;
345 (e) 500 #/cm³; (f) 1000 #/cm³. The corresponding temporal evolution of aerosol charge distributions is shown
346 in Figures S6–S11.

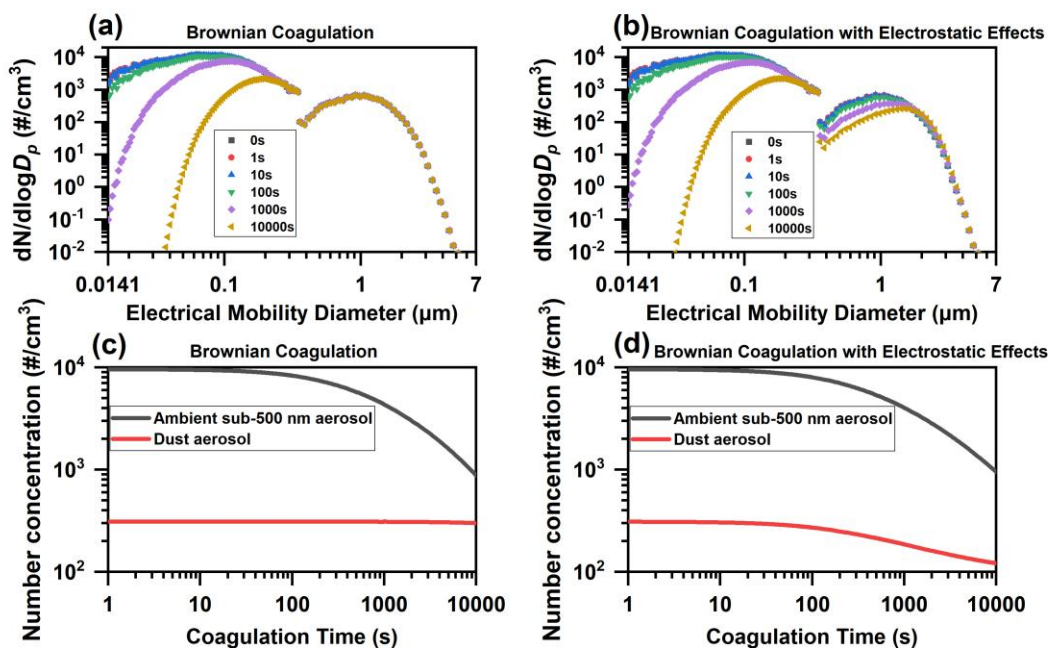
347 The dust aerosols used in this study are more representative of freshly generated dust aerosols. As coagulation
348 and related processes proceed during atmospheric transport, the charge states of dust aerosols are generally
349 expected to decrease. Therefore, the PSD evolution trend shown here is more representative of dust source
350 regions and near-source conditions. However, in real atmospheric transport, dust plumes may continuously
351 mix with newly emitted or entrained aerosols that retain relatively high initial charges. Such continuous input
352 could delay charge decay and sustain stronger electrostatic coagulation over a longer timescale, thereby
353 affecting PSD evolution during transport. The above discussion suggests that the transition from freshly
354 generated, highly charged dust to more aged and weakly charged dust during atmospheric transport deserves
355 more explicit consideration in future modeling studies.

356 **3.3 PSD evolution of ambient aerosols containing a dust fraction of 300 #/cm³ under Brownian and 357 electrostatic coagulation**

358 This section examines the PSD evolution of ambient aerosols containing a dust fraction of 300 #/cm³ under
359 Brownian and electrostatic coagulation using a mixed aerosol system. The model input consisted of the PSD
360 and charge information for (1) ambient sub-500 nm aerosols assuming a Boltzmann-equilibrium charge
361 distribution, and (2) dust aerosols with a total number concentration of 300 #/cm³. These inputs were used to

362 simulate PSD evolution under Brownian and electrostatic coagulation from 0 to 10000 s. Comparison with a
 363 dust-only scenario indicates that dust PSD evolution remains essentially unchanged under both Brownian
 364 and electrostatic coagulation over 0–10,000 s in the mixed system (Figures 4 and 6).

365 The difference between the PSD evolution of ambient sub-500 nm aerosols under electrostatic and Brownian
 366 coagulation in a mixed system containing a dust fraction of 300 #/cm³ is modest but noticeable. As shown in
 367 Figure 6, under Brownian coagulation the peak number concentrations at 100 and 1000 s are ~11000 and
 368 7700 #/cm³, corresponding to diameters of 71 and 113 nm, whereas under the electrostatic coagulation at the
 369 same times the peak number concentrations are ~10700 and 7100 #/cm³, with the peak diameter unchanged.
 370 These changes in peak number concentration show a maximum difference of ~10%, indicating that dust
 371 aerosols exert only a modest but noticeable influence on the PSD of ambient sub-500 nm aerosols. *Although*
 372 *the magnitude of this difference is modest compared with the much larger the PSD changes of highly charged*
 373 *dust aerosols, the ~10% difference indicates that electrostatic interactions affect the evolution of ambient*
 374 *sub-500 nm aerosols. This effect is environmentally relevant because these aerosols are closely related to*
 375 *aerosol radiative effects and CCN number concentrations. At the same time, it should still be regarded as a*
 376 *secondary effect, as it is much smaller than the PSD changes observed for highly charged dust aerosols*
 377 *themselves.*



378
 379 **Figure 6.** Temporal evolution of the PSD and total number concentration of ambient aerosols, containing a
 380 dust aerosol fraction of 300 #/cm³, simulated at 25 °C. (a) PSD of ambient aerosols under Brownian
 381 coagulation, with the dust fraction primarily concentrated in the size range greater than 0.5 μm . Curves

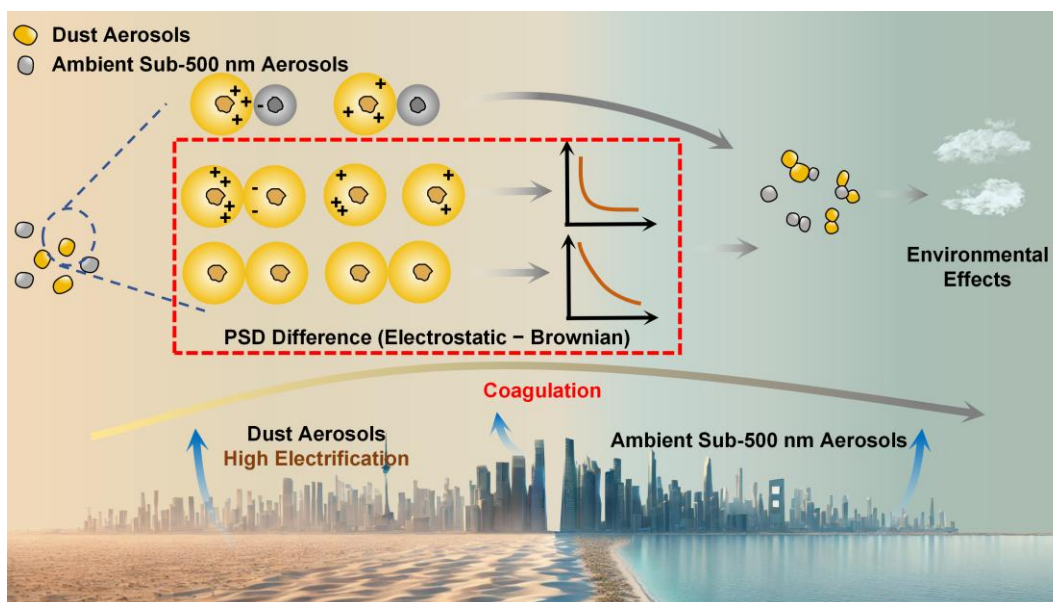
382 correspond to the times indicated in the legend. (b) PSD of ambient aerosols under electrostatic coagulation.
383 (c) Temporal evolution of total number concentrations of ambient sub-500 nm aerosols and dust aerosols
384 under Brownian coagulation. (d) Same as (c), but for electrostatic coagulation.

385 The rate of electrostatic coagulation between dust aerosols and ambient sub-500 nm aerosols first increases
386 and then decreases on hourly timescales. Specifically, during the early stage of electrostatic coagulation, the
387 number concentration of ambient sub-500 nm aerosols declines markedly faster than under Brownian
388 coagulation. However, by 10000 s, the peak number concentration under electrostatic coagulation is even
389 slightly higher than under Brownian coagulation (Figure 6a, b). Mechanistically, high initial dust aerosol
390 concentration increases collision frequency, and high charge enhances Coulomb interactions, which together
391 accelerate coagulation within dust and with ambient sub-500 nm aerosols. As time progresses, dust aerosol
392 concentration and charge decrease (Figure S9), thus reducing electrostatic coagulation with ambient sub-500
393 nm aerosols. This indicates that the electrostatic enhancement of coagulation between dust aerosols and
394 ambient sub-500 nm aerosols is strongly time-dependent and gradually diminishes during long-range
395 transport.

396 It should be noted that, in the mixed aerosol system, the numerical mass loss is more pronounced for
397 coagulation between dust aerosols and ambient sub-500 nm aerosols because of their large size difference.
398 This mass loss mainly arises from the representation of a physically continuous increase in aerosol volume,
399 and thus equivalent diameter, using discrete size bins in the sectional coagulation model. When a dust aerosol
400 coagulates with a much smaller ambient sub-500 nm aerosol, the equivalent-volume diameter of the
401 coagulation product may increase only slightly and may still remain within the original dust aerosol size bin
402 rather than entering the next larger bin. For example, when a 1.085 μm dust aerosol coagulates with a 21.7
403 nm ambient sub-500 nm aerosol, the equivalent-volume diameter of the coagulation product is only
404 approximately 1.085003 μm , which is still below the next larger size bin of 1.166 μm . Therefore, the
405 coagulation product remains assigned to the original 1.085 μm dust aerosol size bin, and the small increase
406 in aerosol volume is not fully reflected as a rightward shift of the dust aerosol PSD. Assuming constant
407 aerosol density and the cubic relationship between aerosol mass and aerosol diameter, a ~10–20% mass loss
408 corresponds to only a ~3%–7% equivalent-diameter difference because aerosol mass scales with the cube of
409 aerosol diameter. Thus, this numerical uncertainty mainly affects the quantitative magnitude of the dust
410 aerosol PSD shift, but is unlikely to alter the qualitative differences in PSD evolution between Brownian
411 coagulation and electrostatic coagulation in the mixed aerosol system.

412 To summarize these processes, Figure 7 provides a conceptual comparison of the two coagulation
413 mechanisms. Enhanced Coulomb interactions among highly charged dust aerosols promote faster coagulation

414 and accelerate number concentration decay, while interactions with ambient sub-500 nm aerosols produce
415 smaller but still observable PSD changes. These results indicate that electrostatic effects may play an
416 important role in shaping aerosol size distributions and their atmospheric impacts.



417

418 **Figure 7.** Conceptual schematic illustrating the contrasting PSD evolution under electrostatic and Brownian
419 coagulation. The nonequilibrium bipolar high-charge state of dust aerosols enhances the effective coagulation
420 rate via Coulomb interactions, accelerating PSD evolution and number concentration decay. Highly charged
421 dust aerosols also modestly accelerate coagulation among ambient sub-500 nm aerosols.

422 4 Conclusions

423 Air quality models usually omit the charge term in the coagulation kernel, thereby neglecting Coulomb
424 interactions during collisions of charged aerosols. In this study, a dedicated DMA–APS configuration is used
425 to retrieve size-resolved single-particle charge distributions for dust aerosols, providing key inputs resolved
426 by particle size and charge amount to the coagulation model. For a dust-only scenario at typical
427 environmental concentrations (300 \#/cm^3), over 0–10000 s the PSD remains essentially unchanged under
428 Brownian coagulation, whereas under electrostatic coagulation the peak diameter shifts from ~ 0.9 to 1.5 \mu m
429 and the peak number concentration decreases by $\sim 64\%$, demonstrating that the PSD evolution of dust aerosols
430 on hourly timescales clearly differs between Brownian and electrostatic coagulation. These results
431 demonstrate that Coulomb interactions can substantially influence the coagulation of highly charged aerosols
432 and must therefore be included explicitly in the coagulation kernel.

433 Given that dust aerosols in the atmosphere mix with abundant ambient sub-500 nm aerosols, it is necessary
434 to quantify how highly charged dust aerosols modify the PSD evolution of ambient aerosols under Brownian
435 versus electrostatic coagulation. When ambient sub-500 nm aerosols are introduced, dust PSD evolution
436 shows no detectable change relative to the dust-only scenario under both Brownian and electrostatic
437 coagulation. Electrostatic coagulation by dust aerosols exerts modest but measurable effects on ambient sub-
438 500 nm aerosols, leading to ~10% differences in peak number concentration relative to Brownian coagulation.

439 Overall, PSD evolution under electrostatic coagulation differs from Brownian coagulation and exhibits
440 pronounced temporal and spatial dependence in systems containing highly charged aerosols. These results
441 indicate that assessments of radiative effects, cloud droplet formation and aerosol deposition should explicitly
442 account for aerosol charge, particularly for highly charged aerosol populations.

443

444 **Code and data availability**

445 All data supporting the findings are archived at Mendeley Data (<https://doi.org/10.17632/n8ys5rzcty.1>). The
446 MATLAB analysis and simulation code and configuration files are included in the same Mendeley Data
447 record. Any additional information is provided in the Supplement. During peer review, access is provided
448 via the private Mendeley Data link; the record will be made public upon publication.

449 **Author contributions**

450 XW conceptualized the study, supervised the project, provided scientific guidance, and led the writing and
451 revision of the manuscript. XL revised and edited the manuscript. LQ conducted the experiments, processed
452 the data, developed the numerical model, and wrote the manuscript. RZ contributed to the construction of the
453 experimental setup, data processing, and the preliminary development of the model framework. All other co-
454 authors participated in the experiments and contributed to the discussion and revision of the manuscript.

455 **Competing interests**

456 The authors declare that they have no competing interests.

457 **Acknowledgements**

458 We thank R. Losno for sharing the SyGAVib design details.

459 **Financial support**

460 This work was supported by the National Natural Science Foundation of China (grant no. 42377090) and the
461 Shanghai Natural Science Foundation (grant no. 23ZR1479700).

462 **References**

463 Adachi, M., Okuyama, K., and Kousaka, Y.: Electrostatic coagulation of bipolarly charged aerosol particles,
464 Journal of Chemical Engineering of Japan, 14, 467–473, <https://doi.org/10.1252/JCEJ.14.467>, 1981.

465

466 Chen, S., Zhao, D., Huang, J., He, J., Chen, Y., Chen, J., Bi, H., Lou, G., Du, S., Zhang, Y., and Yang, F.:
467 Mongolia contributed more than 42% of the dust concentrations in northern China in March and April 2023,
468 *Advances in Atmospheric Sciences*, 40, 1549–1557, <https://doi.org/10.1007/s00376-023-3062-1>, 2023.

469 Cimarelli, C. and Genareau, K.: A review of volcanic electrification of the atmosphere and volcanic lightning,
470 *Journal of Volcanology and Geothermal Research*, 422, 107449,
471 <https://doi.org/10.1016/j.jvolgeores.2021.107449>, 2022.

472 Fuchs, N. A.: *The Mechanics of Aerosols*, Pergamon Press, Oxford, 1964.

473 Grell, G. A., Peckham, S. E., Schmitz, R., McKeen, S. A., Frost, G., Skamarock, W. C., and Eder, B.: Fully
474 coupled “online” chemistry within the WRF model, *Atmospheric Environment*, 39, 6957–6975,
475 <https://doi.org/10.1016/j.atmosenv.2005.04.027>, 2005.

476 Harrison, R. G. and Carslaw, K. S.: Ion–aerosol–cloud processes in the lower atmosphere, *Reviews of*
477 *Geophysics*, 41, 1012, <https://doi.org/10.1029/2002RG000114>, 2003.

478 Hoppel, W. A., Anderson, R. V., and Willett, J. C.: Atmospheric electricity in the planetary boundary layer,
479 in: *The Earth’s Electrical Environment*, 149–165, National Academy Press, Washington, D.C., 1986a.

480 Israel, H.: *Atmospheric Electricity*, Vol. 1, Israel Program for Scientific Translations, Jerusalem, distributed
481 by the National Science Foundation, Washington, D.C., 1970.

482 Israel, H.: *Atmospheric Electricity*, Vol. 2, Israel Program for Scientific Translations, Jerusalem, distributed
483 by the National Science Foundation, Washington, D.C., 1973.

484 Kok, J. F., Adebisi, A. A., Albani, S., Balkanski, Y., Checa-Garcia, R., Chin, M., Colarco, P. R., et al.:
485 Improved representation of the global dust cycle using observational constraints on dust properties and
486 abundance, *Atmospheric Chemistry and Physics*, 21, 8127–8167, <https://doi.org/10.5194/acp-21-8127-2021>,
487 2021.

488 Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R. M., Norford, L., and
489 Britter, R.: Ultrafine particles in cities, *Environment International*, 66, 1–10,
490 <https://doi.org/10.1016/j.envint.2014.01.013>, 2014.

491 Lee, Y. H., Chen, K., and Adams, P. J.: Development of a global model of mineral dust aerosol microphysics,
492 *Atmospheric Chemistry and Physics*, 9, 2441–2458, <https://doi.org/10.5194/acp-9-2441-2009>, 2009.

493 Li, Y., Chen, X., and Jiang, J.: Measuring size distributions of atmospheric aerosols using natural air ions,
494 *Aerosol Science and Technology*, 56, 655–664, <https://doi.org/10.1080/02786826.2022.2060795>, 2022.

495 Liu, B. Y. H. and Pui, D. Y. H.: Equilibrium bipolar charge distribution of aerosols, *Journal of Colloid and*
496 *Interface Science*, 49, 305–312, [https://doi.org/10.1016/0021-9797\(74\)90366-X](https://doi.org/10.1016/0021-9797(74)90366-X), 1974.

497 Ma, Xiewen, Gao, Qiangqian, Jiang, Xinghua, Chen, Shaodong, Gan, Yugi, Zhang, Tao, Lu, Xiaohui, and
498 Wang, Xiaofei.: Direct effects of air humidity on dust aerosol production: Evidence for the surprising role of

499 electrostatic forces, *Geophysical Research Letters*, 50, e2023GL103639,
500 <https://doi.org/10.1029/2023GL103639>, 2023.

501 Mallios, Sotirios A., Daskalopoulou, Vasiliki, and Amiridis, Vassilis.: Modeling of the electrical interaction
502 between desert dust particles and the Earth's atmosphere, *Journal of Aerosol Science*, 165, 106044,
503 <https://doi.org/10.1016/j.jaerosci.2022.106044>, 2022.

504 Maring, H., Savoie, D. L., Izaguirre, M. A., Custals, L., and Reid, J. S.: Mineral dust aerosol size distribution
505 change during atmospheric transport, *Journal of Geophysical Research: Atmospheres*, 108, 8592,
506 <https://doi.org/10.1029/2002JD002536>, 2003.

507 Morawska, L., Ristovski, Z., Jayaratne, E. R., Keogh, D. U., and Ling, X.: Ambient nano and ultrafine
508 particles from motor vehicle emissions: Characteristics, ambient processing and implications on human
509 exposure, *Atmospheric Environment*, 42, 8113–8138, <https://doi.org/10.1016/j.atmosenv.2008.07.050>, 2008.

510 Mu, Feifei and Fiedler, Stephanie.: How much do atmospheric depressions and Mongolian cyclones
511 contribute to spring dust activities in East Asia?, *npj Climate and Atmospheric Science*, 8, Article number
512 51, <https://doi.org/10.1038/s41612-025-00929-w>, 2025.

513 Oron, Alexander and Seinfeld, John H.: The dynamic behavior of charged aerosols: II. Numerical solution
514 by the sectional method, *Journal of Colloid and Interface Science*, 133, 66–79, [https://doi.org/10.1016/0021-9797\(89\)90282-8](https://doi.org/10.1016/0021-9797(89)90282-8), 1989.

515

516 Quan, L.: Critical Role of Dust Induced Electrostatic Coagulation in the Evolution of Aerosol Size
517 Distributions in the Atmosphere [Dataset], *Mendeley Data*, Version 1,
518 <https://data.mendeley.com/datasets/n8ys5rzcty/1>, 2026.

519 Pöschl, U.: Atmospheric aerosols: Composition, transformation, climate and health effects, *Angewandte*
520 *Chemie International Edition*, 44, 7520–7540, <https://doi.org/10.1002/anie.200501122>, 2005.

521 Qu, Zhiqiang, Trabelsi, Zied A., Losno, Roseline, Monna, Fabrice, Nowak, Stephan, Masmoudi, Mohamed,
522 and Quisefit, Jean-Paul.: A laboratory dust generator applying vibration to soil sample: Mineralogical study
523 and compositional analyses, *Journal of Geophysical Research: Atmospheres*, 125, e2019JD032224,
524 <https://doi.org/10.1029/2019JD032224>, 2020.

525 Ramnarine, E., Kodros, J. K., Hodshire, A. L., Lonsdale, C. R., Alvarado, M. J., and Pierce, J. R.: Effects of
526 near-source coagulation of biomass-burning aerosols on global predictions of aerosol size distributions and
527 implications for aerosol radiative effects, *Atmospheric Chemistry and Physics*, 19, 6561–6577,
528 <https://doi.org/10.5194/acp-19-6561-2019>, 2019.

529 Rose, C., Collaud Coen, M., Andrews, E., Lin, Y., Bossert, I., Lund Myhre, C., Tuch, T., Wiedensohler, A.,
530 Fiebig, M., Aalto, P., et al.: Seasonality of the particle number concentration and size distribution: A global

531 analysis retrieved from the network of Global Atmosphere Watch (GAW) near-surface observatories,
532 Atmospheric Chemistry and Physics, 21, 17185–17223, <https://doi.org/10.5194/acp-21-17185-2021>, 2021.

533 Shao, J. and Mao, J.: Dust particle size distributions during spring in Yinchuan, China, *Advances in*
534 *Meteorology*, 2016, Article ID 4050240, <https://doi.org/10.1155/2016/6940502>, 2016.

535 Tammet, H., Hörrak, U., Laakso, L., and Kulmala, M.: Factors of air ion balance in a coniferous forest
536 according to measurements in Hyytiälä, Finland, *Atmospheric Chemistry and Physics*, 6, 3377–3390,
537 <https://doi.org/10.5194/acp-6-3377-2006>, 2006.

538 Tegen, I. and Lacis, A. A.: Modeling of particle size distribution and its influence on the radiative properties
539 of mineral dust aerosol, *Journal of Geophysical Research: Atmospheres*, 101, 19237–19244,
540 <https://doi.org/10.1029/95JD03610>, 1996.

541 Tigges, L., Wiedensohler, A., Weinhold, K., Gandhi, J., and Schmid, H.-J.: Bipolar charge distribution of a
542 soft X-ray diffusion charger, *Journal of Aerosol Science*, 90, 77–86,
543 <https://doi.org/10.1016/j.jaerosci.2015.07.002>, 2015.

544 Xie, H., Wang, Z., Luo, T., Yang, K., Zhang, D., Zhou, T., Yang, X., Liu, X., and Fu, Q.: Seasonal variation
545 of dust aerosol vertical distribution in Arctic based on polarized micropulse lidar measurement, *Remote*
546 *Sensing*, 14, 5581, <https://doi.org/10.3390/rs14215581>, 2022.

547 Zebel, G.: Zur Theorie des Verhaltens elektrisch geladener Aerosole, *Kolloid-Zeitschrift.*, 157, 37–50, 1958.

548 Zhang, H. and Zhou, Y.-H.: Reconstructing the electrical structure of dust storms from locally observed
549 electric field data, *Nature Communications*, 11, 5072, <https://doi.org/10.1038/s41467-020-18759-0>, 2020.

550 Zhang, R., Lu, X., Wang, L., Chen, J., Chen, D.-R., and Wang, X.: Extremely inexpensive and simple method
551 to remove indoor respiratory aerosols, *Environmental Science & Technology Letters*, 10, 786–791,
552 <https://doi.org/10.1021/acs.estlett.3c00541>, 2023.

553