Supporting Information for

Sulfuric acid-amine nucleation in urban Beijing

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Simplified kinetic model

The schematic diagram of the simplified kinetic model is shown in Fig. S1. The reactions included in this model are as follows:

\[
\begin{align*}
A + B & \rightarrow A_1B_1 & k_1 = \beta_{AB} \\
A_1B_1 & \rightarrow A + B & k_2 = \gamma_1 \\
A_1B_1 + A & \rightarrow A_2B_1 & k_3 = \beta_{AA} \\
2A_1B_1 & \rightarrow A_2B_2 & k_4 = 0.5\beta_{11} \\
A_2B_1 + B & \rightarrow A_2B_2 & k_5 = \beta_{BB} \\
A_2B_2 + A_1B_1 & \rightarrow A_3B_3 & k_6 = \beta_{21} \\
A_3B_3 + A_1B_1 & \rightarrow A_4B_4 & k_7 = \beta_{31} \\
A_4B_4 + A_1B_1 & \rightarrow A_5B_5 & k_8 = \beta_{41} \\
2A_2B_2 & \rightarrow A_4B_4 & k_9 = 0.5\beta_{22} \\
A_1B_1(g) & \rightarrow A_1B_1(p) & k_{10} = CS_1 \\
A_2B_1(g) & \rightarrow A_2B_1(p) & k_{11} = CS_2 \\
A_3B_2(g) & \rightarrow A_2B_2(p) & k_{12} = CS_2 \\
A_3B_3(g) & \rightarrow A_3B_3(p) & k_{13} = CS_3 \\
A_4B_4(g) & \rightarrow A_4B_4(p) & k_{14} = CS_4
\end{align*}
\]

where \( A \) is H_2SO_4, \( B \) is dimethylamine (DMA) or trimethylamine (TMA), \( (g) \) represents the gas phase, \( (p) \) the represents particle phase, \( k_\text{x} \) is the reaction rate and \( x \) is the equation number, \( \beta \) is the collision coefficient, \( \gamma \) is the evaporation rate, and \( CS \) is the condensation sink. The subscripts of \( \beta, \gamma, \) and \( CS \) indicate their corresponding equations. The enhancement of coagulation due to van der Waals forces is considered for \( \beta \) and \( CS \). The Hamaker constant is assumed to be 6.4×10^{-20} \text{ J}. The enhancement factor for the coagulation between molecules or clusters was estimated to be 2.3, and it was estimated to be 1.3 for \( CS \) (Chan and Mozurkewich, 2001; Kürten et al., 2018; Stolzenburg et al., 2019). The correction factor of 2.3 agrees with the results obtained by atomistic simulation (Halonen et al., 2019).

The concentrations of \( A_{1,\text{tot}}, B, \) \( CS \), and the ambient temperature are used as the input of this model. \( A_{1,\text{tot}} \) refers to all the sulfuric acid monomers regardless of their base number. \( CS \) was calculated using the measured aerosol size distributions and the sticking probability for every collision between a particle and a cluster is assumed to be 100 %. The value of \( CS \) varies with clusters because of their varying diameters (Lehtinen et al., 2007). The value of \( \gamma \) was calculated according to the theoretical standard molar Gibbs free energy of reaction obtained by quantum chemistry calculation (Ortega et al., 2012).

The influence of temperature on \( \gamma \) is accounted for using the following formula:

\[
\frac{\Delta f G_m^0(T_1)}{T_1} = \frac{\Delta f G_m^0(T_0)}{T_0} - \int_{T_0}^{T_1} \frac{\Delta f H_m^0}{T^2} dT
\]

where \( \Delta f G_m^0 \) is the standard molar Gibbs free energy of formation (of \( A_1B_1 \)), \( T_1 \) is the targeted temperature, \( T_0 = 298.15 \text{ K} \), \( \Delta f H_m^0 \) is the standard molar enthalpy of formation.

The \( \Delta f G_{mA1B1}^0 \) is assumed to be -14.0 kcal/mol, which is higher than the value of -13.5 kcal/mol reported in Myllys et al.
(2019) but lower than the values of -14.4 and -15.4 kcal/mol reported in Ortega et al. (2012). This value was chosen to fit the measured H₂SO₄ dimer concentration and particle formation rate of 1.4 nm particles. Due to the measurement uncertainties, it is difficult to conclude that -14.0 kcal/mol is more accurate than -13.5 or -14.4 kcal/mol for Δ_{G_{m,A1B1}}^{0}, yet we use -14.0 kcal/mol for its better accordance with the measurements.

Considering the fast conversion between A and A₁B₁, Eqs. S1 and S2 are assumed to be at a quasi-steady state. Hence, the concentrations of A and A₁B₁ were calculated using Eq. 1. For A₂B₁, A₂B₂, A₃B₃, and A₄B₄, their concentration change rates derived from Eq. S3-S14 are shown in Eq. S16-S20 and their concentrations are solved numerically in the simplified kinetic model.

\[
\frac{d[A_1B_1]}{dt} = k_1[AB] - k_2[A_1B_1] - k_3[A_1B_1][A] - 2k_4[A_1B_1]^2 - k_6[A_2B_2][A_1B_1] - k_7[A_3B_3][A_1B_1] - k_8[A_4B_4][A_1B_1] - k_9[A_1B_1] - k_{10}[A_1B_1] \tag{S16}
\]

\[
\frac{d[A_2B_1]}{dt} = k_3[A_1B_1][A] - k_5[A_2B_1][B] - k_{11}[A_2B_1] \tag{S17}
\]

\[
\frac{d[A_2B_2]}{dt} = k_4[A_1B_1]^2 + k_5[A_2B_1][B] - k_6[A_2B_2][A_1B_1] - 2k_9[A_2B_2]^2 - k_{12}[A_2B_2] \tag{S18}
\]

\[
\frac{d[A_3B_2]}{dt} = k_6[A_2B_2][A_1B_1] - k_7[A_3B_3][A_1B_1] - k_{13}[A_3B_3] \tag{S19}
\]

\[
\frac{d[A_4B_3]}{dt} = k_7[A_3B_3][A_1B_1] + k_9[A_2B_2]^2 - k_8[A_4B_4][A_1B_1] - k_{14}[A_4B_4] \tag{S20}
\]

The formation rate of A₄B₄ is taken as the simulated particle formation rate, J_{A₄B₄}, and it was calculated using Eq. S21. Note that according to this simulation, during the campaign in urban Beijing, the clustering of A₂B₂ contributes only a minor proportion to J_{A₄B₄}.

\[
J_{A₄B₄} = k_7[A_3B_3][A_1B_1] + k_9[A_2B_2]^2 \tag{S21}
\]

### Derivation of equations 1 and 2 in the main text

Although J_{A₄B₄} is numerically solved in the simplified model, an illustrative analytical solution based on a series of approximations for J_{A₄B₄} is given below for a better understanding of Eqs. 1 and 2 in the main text. Putting the time derivative terms on the left-hand sides of Eqs. S16-S20 to zero yields the following steady-state concentrations of these H₂SO₄-amine clusters:

\[
[A_1B_1] = \frac{k_1[AB]}{k_2 + k_3[A] + 2k_4[A_1B_1] + k_6[A_2B_2] + k_7[A_3B_3] + k_8[A_4B_4] + k_{10}} \approx \frac{k_1[AB]}{k_2 + k_{10}} \tag{S22}
\]

\[
[A_2B_1] = \frac{k_3[A_1B_1][A]}{k_5[B] + k_{11}} \tag{S23}
\]

\[
[A_2B_2] = \frac{k_4[A_2B_1]^2 + k_5[A_2B_1][B]}{k_6[A_1B_1] + 2k_9[A_2B_2] + k_{12}} \approx \frac{k_4[A_2B_1]^2 + k_5[A_2B_1][B]}{k_{12}} \tag{S24}
\]

\[
[A_3B_3] = \frac{k_6[A_2B_2][A_1B_1]}{k_7[A_1B_1] + k_{13}} \approx \frac{k_6[A_2B_2][A_1B_1]}{k_{13}} \tag{S25}
\]
Due to the comparatively high CS in urban Beijing, the cluster growth rates are usually much smaller than their loss rates. As a result, the solution for the steady-state concentrations of H₂SO₄-amine clusters can be simplified as above. Such simplifications are reasonable for the ambient conditions during this campaign (indicated by the horizontal coordinate in Fig. 4).

Since the concentrations of A and A₁B₁ are assumed to be at the steady-state and the sum of their concentrations is equal to the concentration of A₁,tot, the relationship between the concentrations of A₁,tot and A₁B₁ can be readily obtained according to Eq. S22:

$$\frac{[A_1B_1]}{[A_{tot}]} = \frac{k_1[B]}{k_2 + k_{10} + k_1[B]} = \frac{\beta_{AB}[B]}{\gamma_1 + CS_1 + \beta_{AB}[B]} : = \eta$$  (S27)

Combining Eq. S22-S25, the simplified analytical solution for J₄₈B₄ is:

$$J_{A_4B_4} = \frac{k_4 k_5 k_7}{k_{12} k_{13}} [A_{1,tot}]^4 \eta^4 \left[ 1 + \frac{k_3 (1 - \eta)}{k_4} \frac{[B]}{(k_5[B] + k_{11})} \right] + \frac{k_4^2 k_9}{k_{12}} [A_{1,tot}]^4 \eta^4 \left[ 1 + \frac{k_3 (1 - \eta)}{k_4} \frac{[B]}{(k_5[B] + k_{11})} \right]^2$$  (S28)

**Considerations on the simplifications of the model**

This kinetic model is proposed based on both the measured data and the quantum chemistry calculation. The growth of clusters and particles in an H₂SO₄-amine system is driven by the clustering of H₂SO₄ and amine molecules. The detailed growth pathway is determined by the evaporation rate of each AₙBₙ cluster and their concentrations. The evaporation and fission rates of each cluster can be estimated according to quantum chemistry calculation and the reaction pathway under a given condition can thus be derived (McGrath et al., 2012). However, due to the uncertainties in the quantum chemistry calculation, the evaporation rates estimated using different levels of theory deviates from each other in order of magnitudes. For instance, at 298.15 K, the evaporation rate of (H₂SO₄)(amine)₁ in Ortega et al. (2012) and Myllys et al. (2019) was estimated to be 0.14 s⁻¹ and 3.1 s⁻¹ (after correcting the influence of van der Waals force), respectively. Note that the uncertainties in the evaporation rates of larger clusters are perhaps higher because they contain more atoms than AₙB₁ does. Meanwhile, it is difficult to determine the base number of a neutral H₂SO₄-amine cluster using the mass spectrometer (ToF-CIMS) because amine may detach from the H₂SO₄-amine cluster due to ionization, evaporation, and fragmentation during the detection.

As a result, we include only AₙBₙ (n = 1, 2, 3, 4) and A₁B₁ clusters in the simplified model. Considering measurement uncertainties, the simulated results using this simplified model were found to agree with the measured data (Figs. 1, 2, and 3). The stability of A₂B₁ is supported by both the quantum chemistry results (Ortega et al., 2012; Myllys et al., 2019). The estimated relative stability of AₙBₙ (n = 3, 4) under the ambient conditions is still not clear due to the uncertainties of quantum chemistry calculation. For instance, the total evaporation (including monomer evaporation and fission) rates of A₃B₂ were estimated to be 8.3 s⁻¹ and 0.6 s⁻¹ at 298.15 K in Ortega et al. (2012) and Myllys et al. (2019), respectively. These values indicate that A₃B₂ is perhaps unstable or semi-stable in the ambient conditions. Due to the measurement uncertainties, it is difficult to estimate the contribution of A₃B₂ contribution to total H₂SO₄ trimer concentration by comparing the measured
data and simulation results. Hence, $A_{n}B_{m}$ ($n = 3, 4$) are not included in the simplified model. Other $A_{n}B_{m}$ clusters in addition to $A_{2}B_{2}$ and $A_{3}B_{3}$ are much more unstable compared to $A_{2}B_{2}$, e.g., the evaporation rate of $A_{2}B_{1}$ was estimated to be $8.5 \text{ s}^{-1}$ and $103 \text{ s}^{-1}$ at 298.15 K in Ortega et al. (2012) and Myllys et al. (2019), respectively.

As mentioned in the above section and the main text, the depletion of an $\text{H}_2\text{SO}_4$-amine cluster due to its growth is neglected in Eqs. 1 and S22 – S26. We use the example of $A_{1}B_{1}$ to show that this approximation is reasonable in the polluted atmospheric boundary layer. Note that this approximation is used when deriving Eq. 1 but not in the model. Under the typical condition in this field campaign, e.g., $[A_{1,\text{tot}}] = 5 \times 10^6 \text{ cm}^{-3}$, $CS = 1.7 \times 10^{-2} \text{ s}^{-1}$, DMA = 1.8 ppt, $T = 281$ K, and the values of $k_3[A]$ and $2k_4[A_{1}B_{1}]$ in Eq. S22 are approximately $4.2 \times 10^{-3} \text{ s}^{-1}$ and $2.0 \times 10^{-3} \text{ s}^{-1}$, respectively. These values are an order of magnitude smaller than $k_{2} \left( \gamma_1 = 0.11 \text{ s}^{-1} \right)$ and $k_{10} \left( CS = 1.7 \times 10^{-2} \text{ s}^{-1} \right)$. The concentrations of $\text{H}_2\text{SO}_4$ trimer and tetramer are orders of magnitudes lower than $\text{H}_2\text{SO}_4$ dimer concentrations in urban Beijing, hence, the values of $k_{6}[A_{2}B_{2}]$ and $k_{7}[A_{3}B_{3}]$ are even smaller compared to $k_{2}$ and $k_{10}$. This estimation is supported by the horizontal position of the measured data in Fig. 4. Similarly, the evaporation of some stable clusters, e.g., $A_{2}B_{2}$, is neglected because its value is orders of magnitudes smaller than the CS in urban Beijing.

### Scaling of formation rate in Figure 3

In Eqs. S28, $k_4$, $k_6$, $k_7$, and $k_9$ are (half of) the collision coefficients between clusters and they are proportional to $\beta_{11}$, $k_{12}$ and $k_{13}$ are coagulation sinks and they are proportional to CS. The term $1 + k_3(1 - \eta)k_5[B]/[k_4\eta(k_5[B] + k_{12})]$ is dependent on amine concentration and it approaches 1 when [B] increases. Hence, it can be approximated that the formation rate of $A_{1}B_{1}$ clusters is proportional to $[A_{1,\text{tot}}]^{3}$ and $CS^{-2}$. Figures 3a and S7 below indicate that the power of $[A_{1,\text{tot}}]$ should 3.6 instead of 4 for urban Beijing, yet this minor difference does not significantly affect the conclusions. The size of an $A_{4}B_{4}$ cluster ($B$ = DMA) was estimated to be ~1.4 nm (Thomas et al., 2016). Since $[A_{1,\text{tot}}]$ and CS are important factors determining the formation rate, the measured $J_{1,4}$ has to be scaled with respect to them before comparison. For example, a scaling method for CS is given below:

$$J_{1,4,\text{scaled}} = \frac{J_{1,4,\text{measured}} \cdot CS^2}{CS_{\text{ref}}^2} \quad (S29)$$

where $J_{1,4,\text{measured}}$ and $J_{1,4,\text{scaled}}$ are the measured and scaled formation rates of 1.4 nm particles, respectively; CS is the measured condensation sink; $CS_{\text{ref}}$ is the reference condensation sink and it is chosen as 0.017 s$^{-1}$ in Fig. 1, which is a typical value (the median value during NPF events) in urban Beijing during this campaign. The values of the scaled formation rates are mainly affected by $\text{H}_2\text{SO}_4$ concentration and amine concentrations.

### Analytical solution for the model in clean environments

The above discussion is based on the assumption of a high CS, and the approximate solution of $J_{A_{2}B_{1}}$ is given in Eq. S28. However, in clean environments with low CS, the sink for $\text{H}_2\text{SO}_4$-amine clusters is usually determined by their condensation growth rather than the coagulation scavenging. Considering that the monomer concentration is much higher than the concentrations of dimer and trimer, Eq. 22-25 is simplified to obtain an approximate analytical solution that applies for clean environments:
\[ [A_1 B_2] \approx \frac{k_1[A][B]}{k_2 + k_3[A] + 2k_4[A_1 B_4] + k_{10}} \quad (S30) \]

\[ [A_2 B_1] = \frac{k_3[A_1 B_1][A]}{k_5[B] + k_{11}} \quad (S31) \]

\[ [A_2 B_2] = \frac{k_4[A_1 B_1]^2 + k_5[A_2 B_1][B]}{k_6[A_1 B_1] + 2k_9[A_2 B_2] + k_{12}} \quad (S32) \]

\[ [A_3 B_3] = \frac{k_6[A_2 B_2][A_1 B_1]}{k_7[A_1 B_1] + k_{13}} \quad (S33) \]

The solutions for Eq. S32 and S34 are:

\[ [A_1 B_1] = \frac{\sqrt{(k_1[B] + k_2 + k_3[A_{1,\text{tot}}] + k_{10})^2 + 4k_1(2k_4 - k_3)[A_{1,\text{tot}}][B]}}{4k_4 - 2k_3} \]

\[ - \frac{k_1[B] + k_2 + k_3[A_{1,\text{tot}}] + k_{10}}{4k_4 - 2k_3} \quad (S34A) \]

or

\[ [A_2 B_1] \approx \frac{k_1[B]}{k_1[B] + k_2 + k_3[A_{1,\text{tot}}] + k_{10}}[A_{1,\text{tot}}] \quad (assuming \ k_3 = 2k_4) \quad (S34B) \]

\[ [A] = [A_{1,\text{tot}}] - [A_1 B_1] \quad (S35) \]

\[ [A_2 B_2] = \frac{\sqrt{k_6[A_1 B_1] + k_{12})^2 + 8k_9(k_4[A_1 B_1]^2 + k_5[A_2 B_2][B])}}{4k_9} \]

\[ - \frac{k_6[A_1 B_1] + k_{12}}{4k_9} \quad (S36) \]

The expression for \( J_{A_4 B_4} \) is:

\[ J_{A_4 B_4} = k_7[A_3 B_3][A_1 B_1] + k_9[A_2 B_2]^2 \quad (S37) \]

The input for Eq. S37 are \([A_{1,\text{tot}}], [B] \), and \( k_1-k_{13} \) which are mainly influenced by CS and T. \([A_1 B_1], [A], [A_2 B_1], [A_3 B_2] \), and \([A_3 B_3] \) are given in Eqs. S34, S35, S31, S36, and S33, respectively. The values of \( k_1-k_{13} \) are indicated in Eqs. S1-S13. Equation S37 is more accurate than Eq. S28 because Eq. S37 does not neglect the sinks due to condensation growth. However, note that Eq. S37 is derived based on a balance assumption. When the NPF period is shorter than the period for the clusters to reach their steady-state concentrations, Eq. S37 will overestimate the formation rate.
Supporting figures

Figure S1: (a) Time series and (b) a scatter plot of the (H$_2$SO$_4$)$_{1, tot}$ concentration measured by a high-resolution ToF-CIMS and a long ToF-CIMS. The ratio of the (H$_2$SO$_4$)$_{1, tot}$ concentration measured by the long ToF-CIMS to that of the high-resolution ToF-CIMS is 1.4±0.3, where 0.3 is the standard deviation. According to (b), the uncertainty of the H$_2$SO$_4$ measured in this study was estimated to be 100%.
Figure S2: The potential systematic errors for (a) Fig. 1a. and (b) Fig. 1b. The error bar indicates the standard deviation of data due to systematic errors. The uncertainties of CS, [(H$_2$SO$_4$)$_{1,\text{tot}}$, [(H$_2$SO$_4$)$_{2,\text{tot}}$, and $J_{1.4}$ are detailed in the main text. The uncertainty of $[(\text{H}_2\text{SO}_4)_{1,\text{tot}}]^2/\text{CS}$ was estimated according to the formula for error propagation,

$$\sigma \left\{ \frac{[(\text{H}_2\text{SO}_4)_{1,\text{tot}}]^2}{\text{CS}} \right\} = \sqrt{(2\sigma [(\text{H}_2\text{SO}_4)_{1,\text{tot}}])^2 + (\sigma(\text{CS}))^2},$$

where $\sigma$ indicates the relative error. The uncertainty range of simulation was estimated using the evaporation rate of (H$_2$SO$_4$)(amine)$_1$ from different literature (Ortega et al., 2012; Myllys et al., 2019). oB97X-D/6-31++G** and RICC2B3 indicate the evaporation rates therein. The uncertainty in the amine measurement is included in the simulation, i.e., the higher simulation curve uses [amine]×(1+$\sigma_{\text{amine}}$) as the model input while the low curve uses [amine]×(1-$\sigma_{\text{amine}}$).
Figure S3: The correlation between the simulated and measured particle formation rates \( (J_{1.4}) \). The \( R^2 \) value was calculated using logarithmic values. This figure uses the same dataset as Fig. 3b. The temporal resolution of the raw data is 5 min, which is determined by the aerosol size spectrometers.
Figure S4: Mass defect plots of (a) neutral clusters measured by a ToF-CIMS and (b) naturally charged clusters measured by an Api-ToF-MS on Feb. 24, 2018. The dot size indicates the ion count number of each corresponding peak per unit volume. The ion counts were averaged between 11:30 and 12:30. The neutral clusters in (a) were charged using a nitrate source and only the chemical species after charging are shown. The red dots represent the measured H$_2$SO$_4$ clusters without amine, while the blue and purple dots represent H$_2$SO$_4$ clusters with amines (or NH$_3$ in (b)). In addition to H$_2$SO$_4$-C$_2$H$_7$N cluster, H$_2$SO$_4$-CH$_5$N and C$_4$H$_7$N clusters were observed for H$_2$SO$_4$ trimers. NH$_3$ was not detected in the neutral clusters in (a). Note that due to the ionization, evaporation, and fragmentation, the amine molecule in a stable neutral H$_2$SO$_4$-amine cluster may detach during the detection by the mass spectrometer (ToF-CIMS). For instance, although (H$_2$SO$_4$)$_3$(DMA)$_1$ is thought to be relatively stable, the charged (HSO$_4^-$)$_3$(DMA)$_1$ is unstable and hence only HSO$_4^-$ and H$_2$SO$_4$NO$_3^-$ were detected. In addition, although a variety of organics were detected, the concentrations of extremely low volatile organic compounds are limited (~1 order of magnitude lower compared to Finnish boreal forest). The volatility of organic compounds was estimated from their molecular formula using the volatility basis set (Donahue et al., 2011; Donahue et al., 2012). Considering the uncertainties in this estimation, the contributions of organic compounds to nucleation and the very initial steps of particle growth are thought to be minor compared to the fast H$_2$SO$_4$-amine clustering process.
Figure S5: The measured formation rate of 1.7 nm particles, $J_{1.7}$, and the simulated $J_{1.7}$ using the organics nucleation mechanism. Only the extremely low volatile organic compounds (ELVOCs) measured by the ToF-CIMS was accounted for in the simulation. The volatility was estimated using the volatility basis set (Donahue et al., 2011; Donahue et al., 2012). The $J_{1.7}$ was simulated using the formula proposed in Kirkby et al. (2016). Note that the simulated $J_{1.7}$ from organics nucleation in this figure is overestimated because the CS in urban Beijing is higher than that in the CLOUD chamber, whereas the empirical formula used for this simulation does not account for the influence of CS on $J_{1.7}$. Besides, ion-induced nucleation contributes majorly the simulated $J_{1.7}$ in this figure, whereas its contribution in the polluted atmosphere is thought to be minor. Considering this overestimation and measurement uncertainties, this figure indicates the organics nucleation is insufficient to explain the high nucleation rates observed in urban Beijing.
Figure S6: The diurnal variations of median (a) number concentration of particle ranging from 1.5 nm to 3 nm ($N_{1.5-3}$) H$_2$SO$_4$ monomer concentration, and H$_2$SO$_4$ dimer concentration; (b) ELVOC concentration and condensation sink (CS); (c) measured particle formation rate ($J_{1.4,\text{meas}}$) and simulated formation rates using the H$_2$SO$_4$-amine nucleation mechanism and the organics nucleation mechanism in ref. (Kirkby et al., 2016). All the variables are normalized by dividing them by their daily maximum concentration. The trend of the measured nucleation (indicated by $N_{1.5-3}$ and $J_{1.4,\text{meas}}$) is consistent with that of H$_2$SO$_4$-amine nucleation (indicated by the measured H$_2$SO$_4$ dimer concentration and the simulated $J_{1.4,H_2SO_4}$), whereas it is inconsistent with that of organics nucleation (indicated by the measured ELVOC concentration and the simulated $J_{1.7,\text{ELVOC}}$). Figures S5 and S6 support that organics nucleation is not the governing nucleation mechanism in urban Beijing.
Figure S7: The power of the simulated formation rate of ~1.4 nm particles to the total concentration of H$_2$SO$_4$ monomers as a function of condensation sink. The curves are obtained at the steady-state. Under a negligible condensation sink, the formation rate of a cluster is approximately equal to its growth rate into the next cluster. Thus, the formation rate under such a condition is approximately equal to that of (H$_2$SO$_4$)$_2$(DMA)$_2$, which is proportional to the square of (H$_2$SO$_4$)$_{1,\text{tot}}$ concentration, i.e., $p = 2$. In contrast, the formation rate of a cluster is approximately equal to its coagulation loss rate under a high condensation sink. Given a fixed DMA concentration, Eqs. S28 indicates that $p = 4$ when the coagulation sink is the governing sink for clusters. The solid curve in this figure resembles the typical H$_2$SO$_4$ and DMA concentrations during this measurement in urban Beijing. At the typical condensation sink and temperature during new particle formation in urban Beijing, e.g., 0.017 s$^{-1}$ and 281 K, the simulated $p$ on the solid line is approximately 3.6.