A dynamic parameterization of sulfuric acid-dimethylamine nucleation and its application in three-dimensional modeling

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Abstract. Sulfuric acid (SA) is a governing gaseous precursor for atmospheric new particle formation (NPF), a major source of global ultrafine particles, in environments studied around the world. In polluted urban atmospheres with high condensation sink (CS), the formation of stable SA-amine clusters, such as SA-DMA clusters, usually initializes intense NPF events. Coagulation scavenging and cluster evaporation are dominant sink processes of SA-amine clusters in urban atmospheres, yet these loss processes are not quantitatively included in the present parameterizations of SA-amine nucleation. We herein report a parameterization of SA-DMA nucleation based on cluster dynamic simulations and quantum chemistry calculations, with certain simplifications to greatly reduce the computational costs. Compared with previous SA-DMA nucleation parameterizations, this new parameterization was able to reproduce the dependences of particle formation rates on temperature and CS. We then incorporated it in a three-dimensional chemical transport model to simulate the evolution of particle number size distributions. Simulation results showed good consistency with the observations in the occurrence of NPF events and particle number size distributions in wintertime Beijing, and represented a significant improvement compared to that using parameterization without coagulation scavenging. Quantitative analysis shows that SA-DMA nucleation contributes significantly to nucleation rates and aerosol population during the 3-D simulations in Beijing (>99% and >60%, respectively). These results broaden the understanding of NPF in urban atmospheres and stress the necessity of including the effects of coagulation scavenging and cluster stability in simulating SA-DMA nucleation in three-dimensional simulations. Representing these processes is thus likely to improve model performance in particle source apportionment and quantification of aerosol effects on air quality, human health, and climate.

1 Introduction

New particle formation (NPF) is the major source of atmospheric particles in terms of their number concentration, which regulates the Earth's radiative balance and affects the climate (Kulmala et al., 2004; Gordon et al., 2017; Merikanto et al., 2009). The transformation from gaseous precursors to stable clusters and particles via nucleation is the initial step of NPF, and new particle formation rate (J) is an essential parameter to characterize NPF intensity (Kulmala, 2003). Although nucleation processes would be suppressed by coagulation scavenging in urban atmospheres with high condensation sink (CS) (Cai and Jiang, 2017; Cai et al., 2017b), intense NPF events have been frequently observed (Wu et al., 2007; Xiao et al., 2015; Deng et al., 2020). Recently increasing evidence has been provided that those intense events are driven by the formation of stable SA-amine clusters (Cai et al., 2022; Jen et al., 2014b; Yin et al., 2021) with a speed close to the collision limit for SA molecules, thus deriving high nucleation rates in urban atmospheres (Cai et al., 2021d; Yao et al., 2018; Chen et al., 2012). Furthermore, other molecules, such as HNO_3 and NH_3, could enhance the SA-DMA nucleation under certain conditions (Liu et al., 2021; Glasoe et al., 2015; Wang et al., 2021). Although a few previous 3-D simulation studies have simulated NPF events in polluted urban atmospheres such as Beijing, they didn't take the SA-amine nucleation into account (Chen et al., 2019; Chen et al., 2021b).Thus, integrating SA-amine nucleation into three-dimensional (3-D) models is essential in extending the understanding of NPF in polluted urban areas and quantifying its underlying impacts on the environment and climate. This requires a quantitative representation of particle formation rates through SA-amine nucleation for 3-D models.

Semi-empirical power-law functions are widely used in SA-relevant nucleation rate studies to fit the experimental data, which has been shown to reproduce the measured J in certain ambient observations or experimental conditions (Riccobono et al., 2014; Dunne et al., 2016; Bergman et al., 2015; Hanson et al., 2017; Semeniuk and Dastoor, 2018; Kurten et al., 2014; Kurten et al., 2018). For SA-amine nucleation, Bergman et al. (2015) and Dunne et al. (2016) have presented semi-empirical parameterizations of good consistencies with chamber and flow-tube experimental results (Almeida et al., 2013; Jen et al., 2014b; Glasoe et al., 2015). In real urban atmospheres, recent advances have shown that coagulation scavenging would greatly suppress concentrations of molecular clusters, and thus the nucleation rates (Cai and Jiang, 2017; Cai et al., 2021c; Cai et al., 2021d; Marten et al., 2022). It has also been addressed that the formation of the smallest SA-amine clusters, which is largely dependent on cluster stability, is the limiting step for SA-amine nucleation rates (Cai et al., 2022). However, the effects of coagulation scavenging and cluster stability vary with the environmental factors, e.g., CS and temperature, while these effects have not been well represented in semi-empirical power-law functions derived from certain experimental systems or ambient environments. Cluster kinetic simulations coupled with quantum chemistry calculations (Mcgrath et al., 2012), which take into account the effects of both coagulation scavenging and cluster stability, have been widely applied in zero-dimensional or one-dimensional simulations of $SA-NH_3$ or SA-amine nucleation (Yang et al., 2021; Lu et al., 2020; Yao et al., 2018; Yu, 2006; Yu and Turco, 2001). Specifically, both cluster kinetic simulations and observations reveal that dimethylamine (DMA) is plausibly most efficient in stabilizing SA clusters and is regarded as the key amine species deriving high particle formation rates in urban atmospheres (Jen et al., 2014b; Cai et al., 2022; Yao et al., 2018; Chen et al., 2012). However, no method with good representations of coagulation scavenging and cluster stabilities has been reported to explicitly simulate the SA-DMA nucleation rates in 3-D chemical transport models.

A challenge in setting up a parameterization based on cluster kinetic simulations for 3-D chemical transport models is to reduce computational costs and yield explicit expressions. A plausible method to reduce computational costs is to omit the unstable clusters with high evaporation rates from the nucleation pathway. Accordingly, different nucleation schemes were presented to represent the dominant source or sink processes of SA-DMA clusters in specific chamber experiments or ambient environments (Lu et al., 2020; Cai et al., 2021d). For polluted urban atmospheres, a kinetic model with a key pathway of particle formation in SA-DMA nucleation was constructed, yielding good predictions of measured SA cluster concentrations and 1.4 nm particle formation rates ($J_{1.4}$) in urban Beijing (Cai et al., 2021d). Application of pseudo-steady-state assumptions

81 is also an alternative method for reducing computational costs and yielding explicit expressions. The NPF occurrence indicator

82 (I) based on the kinetic model with pseudo-steady-state assumptions has shown good consistency in qualitatively estimating

83 the NPF events in urban Beijing and Shanghai (Cai et al., 2021c). These results indicate the potential of deriving an explicit

84 parameterization of particle formation rates by applying pseudo-steady-state assumptions to the kinetic model, although further

85 quantitative analysis is still required to validate this parameterization.

86 In this study, we set up an SA-DMA nucleation parameterization, which is designed for application in 3-D chemical transport

87 models. The parameterization is based on the pseudo-steady-state particle formation rate in the kinetic model, with a full

88 representative of the effects of coagulation scavenging and cluster stability (Cai et al., 2021d). Generally, only four variables

89 (temperature T, CS, gaseous DMA concentrations $[B]$, and concentrations of SA molecules or clusters containing one SA

90 molecule $[SA_{tot}]$) are used in the parameterization, with computational costs greatly reduced. We then implement the

91 parameterization in a 3-D chemical transport model and combine it with an integrated source-sink representation of DMA to

92 simulate the evolution of the particle number size distributions (PNSDs) in wintertime Beijing. The precursor concentrations,

93 PNSDs, NPF occurrence and $J_{1.4}$ show relatively good consistencies between simulations and observations. The simulations

94 show that the SA-DMA nucleation contributes >99% of the $J_{1.4}$ and >60% of the total particle number concentration in

95 wintertime Beijing, respectively. With this parameterization, 3-D chemical transport models could significantly improve the

96 simulation of NPF, especially in urban environments, and thus the effects of NPF on particulate matter pollution or climate.

2 Methods

2.1 Derivation of Parameterized Formation Rate in SA-DMA Nucleation

99 Limited by computational quantum chemistry calculation results, SA-DMA nucleation is commonly simulated in the range of

100 clusters containing not more than 4 SA or 4 DMA molecules (Olenius et al., 2013; Ortega et al., 2012). As unstable clusters

101 would evaporate with higher rates, the formation of larger clusters potentially follows the pathways of the most stable clusters.

102 In addition, as the SA-DMA clusters are increasingly stable along the main pathway of cluster formation, the clusters not

103 smaller than A_4B_4 (hereafter A_mB_n refers to clusters containing m SA and n DMA molecules) is assumed to not evaporate back

104 in these simulations. Although there are uncertainties in the pathways presented based on different quantum chemistry methods,

105 it is well accepted that the A_mB_m (m=1 to 4) and A_2B_1 clusters are relatively stable in the SA-DMA nucleation scheme (Olenius

106 et al., 2017; Olenius et al., 2013; Ortega et al., 2012; Myllys et al., 2019).

107 Based on previous studies under atmospheric conditions, the variation of precursor concentrations, temperature, and CS do

108 not result in large deviations in the main pathway. Previous simulations under different [SA], [DMA], and temperature have

109 shown that the main pathway was similar under the different conditions studied (Olenius et al., 2013). The effect of CS on

110 nucleation pathway is dependent on the relative relationship between the coagulation sink and the evaporation rate of a certain

111 cluster. For most clusters out of the specified pathway, the evaporation rates are much higher than the typical CS range in

112 urban atmospheres (Ortega et al., 2012), therefore such clusters would not dominate the nucleation pathway no matter how

113 low or high the CS is. Thus in this study, the variation of the dominant pathway under different conditions was ignored.

114 Accordingly, the parameterization in this study is derived from the nucleation pathway including A, B and other 5 SA-DMA

115 clusters (A_mB_m (m=1 to 4) and A_2B_1), consistent with a previous study (Cai et al., 2021d). The clusters except A_4B_4 are assumed

116 to be in pseudo-steady states, i.e. the sink due to evaporation, coagulation scavenging, and cluster collision is equal to the

117 source due to the collisions of molecules or smaller clusters. As the A_4B_4 clusters are estimated to be with an electrical mobility

118 diameter of approximately 1.4 nm, the pseudo-steady-state formation rate of A_4B_4 was applied in the parameterization of $J_{1.4}$

119 in this study. Although some studies have revealed that SA-DMA nucleation could also be enhanced by adding other molecules

120 in certain conditions, quantitative analysis of these effects in relevant atmospheric conditions is still lacking, thus in this study,

121 we set up this parameterization only based on SA-DMA binary nucleation.

2.1.1 Derivation of Collision Coefficients, Coagulation Sink, and Evaporation Rates

123 In the nucleation pathway discussed above, A, B, and 5 SA-DMA clusters are included. The collision coefficients between

124 them ($\beta_{i\text{-}j}$) and the evaporation rate of A_1B_1 clusters (γ) vary with T during the simulation. The coagulation sinks ($CoagS_i$) due

125 to the coagulation scavenging of background aerosols are dependent on CS. The work discussed in this section is focused on

126 simplification of the derivation of these parameters to be updated in each simulation time interval to reduce the computational

127 costs.

128 As the involved clusters and molecules are in the free molecular regime (Knudsen number > 10), $\beta_{i\text{-}j}$ in SA-DMA nucleation

129 processes can be calculated based on kinetic gas theory (Seinfeld and Pandis, 1998; Olenius et al., 2013; Ortega et al., 2012):

130 $$\beta_{i\text{-}j} = \left(\frac{3}{4\pi}\right)^{1/6}\left(\frac{1}{m_i}+\frac{1}{m_j}\right)^{1/2}(V_i^{1/3}+V_j^{1/3})^2(6k_bT)^{1/2}E_{ij}, \tag{1}$$

131 where m (kg) and V (m^3) represent the molecular mass and molecular volume, respectively. The density of precursor molecules

132 A and B was assumed to be 1830 and 680 kg m^{-3}, respectively. T (K) represents the temperature. k_b (J K^{-1}) is the Boltzmann

133 constant. Subscripts i and j refer to the index of the clusters or molecules (1 to 7 refer to A, B, A_1B_1, A_2B_1, A_2B_2, A_3B_3, and A_4B_4,

134 respectively, which are involved in the kinetic model). E_{ij} is a dimensionless enhancement factor of the collision rates from

135 Van de Waals forces between i and j. In this study, E_{ij} is assumed to be 2.3 (Chan and Mozurkewich, 2001; Sceats, 1989),

136 within the range of 2.3 to 2.7 predicted by Brownian coagulation models, and consistent with the value used in other cluster

137 dynamics studies (Kurten et al., 2014; Lehtipalo et al., 2016; Stolzenburg et al., 2020).

138 Noting that m_i and V_i are almost independent of the atmospheric conditions and E_{ij} is assumed to be constant, we can normalize

139 different values of $\beta_{i\text{-}j}$ into β, and the normalizing factor is shown in a look-up table (Table S1 in the supporting information

140 (*SI*)) as $G(i,j)$:

141 $$\beta_{i\text{-}j} = \beta G(i, j), \tag{2}$$

142 where β represents the collision coefficients between two A_1B_1 clusters ($\beta_{3\text{-}3}$), and could be calculated as:

143 $$\beta = \beta_0\left(\frac{T}{T_0}\right)^{0.5}, \tag{3}$$

144 where β_0 is the value of β at the standard temperature T_0=298.15 K, constant as 1.126×10^{-15} m^3 s^{-1}.

145 Similarly, $CoagS_i$ could also be normalized to CS using fixed ratios. The size dependent coagulation sink (CoagS) is calculated

146 with a power-law exponent of -1.7, within the typical range of atmospheric aerosols (Lehtinen et al., 2007):

147 $$CoagS_i = CS\left(\frac{V_i}{V_1}\right)^{-\frac{1.7}{3}}=H(i)CS, \tag{4}$$

148 where the dimensionless factors $H(i)$ are also recorded in Table S1 in the *SI*.

149 The evaporation rates of A_1B_1 could be derived based on collision-evaporation equilibrium (Ortega et al., 2012), closely

150 relevant to the free energy barrier to form A_1B_1 clusters (Olenius et al., 2013; Ortega et al., 2012):

151 $$\gamma = \beta_{1\text{-}2}c_{ref}\exp\left(\frac{\Delta G}{k_BT}\right), \tag{5}$$

152 where c_{ref} is the number concentrations under standard conditions (2.46×10^{25} m^{-3}). ΔG is the formation free energies of A_1B_1.

153 Thus if we take $T_0 = 298.15$ as a reference, γ could also be calculated as:

154 $$\gamma = \gamma_0\left(\frac{T}{T_0}\right)^{0.5}\exp\left(\frac{\Delta H}{k_B}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right), \tag{6}$$

155 $\gamma_0 = \gamma_0' \exp(\frac{\Delta G - \Delta G_0}{k_B T_0})$, (7)

156 where γ_0', with the value of 3.33 s⁻¹, is the evaporation rates of A_1B_1 at T_0 with $\Delta G = \Delta G_0 = -13.54$ kcal mol⁻¹. ΔH is the formation

157 enthalpies of A_1B_1. In previous studies, several sets of ΔH and ΔG at specific temperatures were reported based on different

158 quantum chemistry models (Myllys et al., 2019; Ortega et al., 2012; Ge et al., 2020a). Here we use $\Delta H = -24.82$ kcal mol⁻¹ and

159 $\Delta G = -13.54$ kcal mol⁻¹ according to the results in Myllys et al. (2019). If the values of ΔG need to be updated in future

160 application of this parameterization, the values of γ_0 should be updated as well based on Eq. 7. The sensitivity analysis of

161 different values of ΔH and ΔG are discussed in the Results section.

162 Generally, with $G(i,j)$ and $H(i)$ fixed into the parameterization formula, β_{i-j} and $CoagS_i$ could be normalized to β and CS.

163 Additionally, the values of γ and β could be real-time updated at any simulation timestep based on Eqs. 3 and 6.

2.1.2 Formula of the SA-DMA Nucleation Parameterization

165 Applying the pseudo-steady-state assumptions to the key pathway discussed above (Eqs. S1 to S9) and achieving real-time γ

166 (s⁻¹) and β (m³ s⁻¹) (Eqs. 3 and 6), we could derive an explicit formula of the parameterized $J_{1.4}$ in this study (Eq. 8).

167 $J_{1.4} = \frac{\beta\theta[A_1B_1]^4}{2([A_1B_1]+0.39\frac{CS}{\beta})}\left(\frac{0.23\theta'}{[A_1B_1]+0.39\frac{CS}{\beta}}+\frac{1.00}{[A_1B_1]+0.31\frac{CS}{\beta}}\right)$, (8)

168 The above intermediate parameters are calculated as below:

169 $[A_1B_1] = \frac{0.96[B][SA_{tot}]}{0.96[B]+\frac{\gamma}{\beta}+0.86[SA_{tot}]+0.63\frac{CS}{\beta}}$, (9)

170 $\theta = 1+\frac{2[B]}{1.16[B]+0.46\frac{CS}{\beta}}\frac{[SA_{tot}]-[A_1B_1]}{[A_1B_1]}$, (10)

171 $\theta' = \frac{\theta(2.22[A_1B_1]+0.86\frac{CS}{\beta})}{\sqrt{(1.11[A_1B_1]+0.43\frac{CS}{\beta})^2+1.12\theta[A_1B_1]^2+1.11[A_1B_1]+0.43\frac{CS}{\beta}}}$, (11)

172 In Eqs. 8 to 11, the four input variables (T (K), CS (s⁻¹), $[B]$ (m⁻³), $[SA_{tot}]$ (m⁻³)) are shown in bold. Generally, only these four

173 variable parameters are needed for the 3-D chemical transport models. Additionally, compared with directly coupling cluster

174 dynamic simulations into 3-D chemical transport models, the parameterization of pseudo-steady-state $J_{1.4}$ requires much less

175 computational time.

2.2 Incorporating the Parameterization into Updated WRF-Chem/R2D-VBS Model

177 The updated parameterization of SA-DMA nucleation was incorporated in the WRF-Chem (Weather Research and Forecasting

178 model with Chemistry). Before adding the SA-DMA nucleation, we already incorporated seven other NPF mechanisms in the

179 model (Zhao et al., 2020): four inorganic pathways, including binary neutral/ion-induced SA-H₂O nucleation and ternary

180 neutral/ion-induced NH₃-SA-H₂O nucleation; and three organic pathways, including pure-organic neutral/ion-induced organic

181 nucleation and ternary nucleation involving organics and SA. The organic containing nucleation pathways are driven by ultra-

182 and extremely low volatility organic compounds (ULVOC and ELVOC) with O:C > 0.4, converted from monoterpene

183 autoxidation. The chemical transformation and volatility distribution of monoterpene is represented in the model by R2D-VBS

184 (Radical Two-Dimensional Volatility Basis Set framework) with constrained parameters against experiments. More details of

185 the R2D-VBS are given in our previous study (Zhao et al., 2020). The newly formed nano-sized particles and their initial size

186 evolution are accounted in the MOSAIC module by 20 size bins covering 1 nm to 10 μm. It is worth mentioning that the newly

187 formed particles from SA-DMA nucleation are lumped into a lower aerosol size bin in the model than that of other seven

188 pathways. This should be attributed to that our SA-DMA nucleation parameterization are formulated at a 1.4 nm-sized particle

189 formation rate while the remaining ones are fitted based on measured particle formation rates from CLOUD Chamber at a

190 mobility diameter of 1.7 nm. Given that condensation of gaseous SA and DMA on pre-existing aerosols and nucleation occur
191 simultaneously in the real atmosphere, in the model, we then use a time-integrated-averaged concentration of precursors over
192 each time step to drive SA-DMA nucleation. The condensation sink for SA and DMA is calculated according to simulated
193 real-time PNSDs. In addition, the consumption of both SA and DMA concentration during nucleation is also accounted in the
194 model, in order to represent a comprehensive sources-sink simulation scheme of two precursors in combination with other
195 settings.

2.2.1 Sources and Sinks of Dimethylamine in the Updated WRF-Chem/R2D-VBS Model

197 A regional or global bottom-up emission inventory of DMA is currently lacking, mostly due to scarce direct measurements
198 (Yang et al., 2022; Zhu et al., 2022). In previous 3D model studies, amine/NH_3 emission ratios have often been used to estimate
199 amine emissions due to the close correlation between NH_3 and DMA emissions. However, a fixed amine/NH_3 ratio is likely
200 to overestimate the concentrations of amines in rural areas while underestimating those in urban areas, where high
201 concentrations of amines have been reported (Yao et al., 2018; Bergman et al., 2015). Here, a set of source-dependent
202 DMA/NH_3 emission ratio was used to develop the emission inventory of DMA based on (Mao et al., 2018). The ratios for
203 different emission sectors were determined by a source apportionment analysis, based on a simultaneous observation of NH_3,
204 C1-C3 amines, NO_x, and SO_2 and also meteorological factors at a suburban site in Nanjing (Zheng et al., 2015a). We applied
205 the source-dependent emission ratios (0.0070, 0.0018, 0.0015, 0.0100, and 0.0009 for chemical–industrial, other industrial,
206 agricultural, residential, and transportation source types, respectively) to NH_3 emissions in the ABaCAS-EI 2017 (Emission
207 Inventory of Air Benefit and Cost and Attainment Assessment System) for China mainland and the IIASA 2015 emission
208 inventory for other areas to build continental DMA emission inventory (Zheng et al., 2019; Li et al., 2017). In addition, DMA
209 emission for maritime area was developed employing a DMA/NH_3 ratio derived from recent campaigns in offshore areas of
210 China (see details in SI) (Chen et al., 2021a).

211 DMA can be removed from the atmosphere through three main pathways: gas-phase chemical reaction, aerosol uptake, and
212 wet deposition, which are all explicitly considered in our model. For the gas-phase chemical reactions, only oxidation of DMA
213 by •OH is included. Reactions with other oxidants (O_3 and NO_3) are much slower and therefore have negligible effects on
214 DMA concentrations (Ge et al., 2011). The mechanism of DMA concentration depletion by aerosol uptake is still poorly
215 understood, and the key parameter, uptake coefficient γ_u, varies in a wide range depending on many factors such as aerosol
216 composition and relative humidity. In this study, we assumed $\gamma_u = 0.001$, approximately a median value among those reported
217 by recent laboratory measurements (Qiu et al., 2011; Wang et al., 2010). Regarding DMA depletion by wet deposition, the
218 treatment is similar to that of NH_3 based on Henry's Law. The key parameters for above sink processes are summarized in
219 Table S2 in the *SI*.

2.2.2 Configuration of the Updated WRF-Chem/R2D-VBS Model.

221 The WRF-Chem model configured with the SA-DMA nucleation is applied to a domain covering eastern Asia with a horizontal
222 resolution of 27 km, where Beijing is located close to the center. The simulations are performed for two winter months
223 separately (December 2018 and January 2019) with 5 days spin-up run for each month. The ABaCAS-EI 2017 and IIASA
224 2015 emission inventory were used for China mainland and other areas, respectively. The biogenic emission is calculated by
225 the Model of Emissions of Gases and Aerosols from Nature (MEGAN) v2.04 (Guenther et al., 2006). Except for the
226 monoterpene-related gas and aerosol chemistry that is traced by R2D-VBS, the remaining gas- and aerosol chemical processes
227 are simulated by the SAPRC99 gas chemistry scheme coupled with the MOSAIC (Model for Simulating Aerosol Interaction
228 and Chemistry) aerosol module and a one-dimensional VBS set for SOA modeling (Zaveri et al., 2014; Shrivastava et al.,
229 2019; Shrivastava et al., 2011).

230 Four scenario simulations with different configurations of the NPF mechanisms were conducted in this study to examine how
231 the SA-DMA nucleation affects the simulations of aerosol size distribution: 1) 8 NPF mechanisms with the SA-DMA
232 nucleation rate at 1.4 nm (abbr. DMA1.4_Mech8); 2) 8 NPF mechanisms with the SA-DMA nucleation rate at 1.7 nm
233 converted using modified Kerminen-Kulmala equation (Lehtinen et al., 2007) (DMA1.7_Mech8); 3) 7 NPF mechanisms
234 without the SA-DMA nucleation (NoDMA_Mech7); and 4) No NPF mechanism (NoDMA_Mech0). Among them, scenario 1
235 is our "best-case" with a full consideration of available nucleation mechanisms; scenario 2 is set to probe the feasibility to use
236 modified Kerminen-Kulmala equation to simulate the initial particle growth; scenario 3 is the "base-case" representing the
237 performance of the original model; and scenario 4 represents the evolution of aerosol population only contributed by primary
238 emission. Scenarios 3 and 4 were set as controlling groups to assess the role of SA-DMA nucleation and other mechanisms.

239 **2.3 Ambient Measurements**

240 Ambient observations were conducted at an urban site in Beijing from January 2018 to April 2018 and from October 2018 to
241 March 2019. The site is located on the West Campus of Beijing University of Chemical Technology. Details of the observation
242 site can be found in previous studies (Liu et al., 2020; Deng et al., 2020). The concentrations of SA and involving clusters are
243 measured using a chemical ionization high resolution time of flight mass spectrometer (CI-HTOF-MS) and a chemical
244 ionization time of flight mass spectrometer with a long mass analyzer (CI-LTOF-MS) (Bertram et al., 2011; Jokinen et al.,
245 2012). Other details in the sampling configurations have been reported in our previous study (Deng et al., 2020). Amine
246 concentrations are measured using a modified time of flight mass spectrometer (TOF-MS) (Zheng et al., 2015b; Cai et al.,
247 2021b). A weather station was deployed to measure the meteorological data, including ambient temperature, relative humidity
248 and pressure. The PNSDs of particles from 1 nm to 10 μm were measured using a particle size distribution (PSD) and a diethyl
249 glycol-scanning mobility particle sizer (DEG-SMPS) (Jiang et al., 2011; Liu et al., 2016; Cai et al., 2017a). CS is calculated
250 from the measured PNSDs and $J_{1.4}$ is calculated using an improved aerosol population balance formula (Cai and Jiang, 2017).
251 The details of instrument calibrations and data validations can be found in our previous study (Cai et al., 2021b).

252 **3 Results and discussion**

253 **3.1 Validation of Parameterization**

254 The reasonability of pseudo-steady-state assumptions in the SA-DMA nucleation pathway was tested through comparisons
255 between the e-folding time of cluster dynamics (τ) in the kinetic simulation (see details in the *SI*) and the time interval of
256 observational data (30 min in this study). The characteristic equilibrium time of involving clusters and simulated $J_{1.4}$ were
257 shown in Fig. S1 in the *SI*. Generally, in either clean and cold circumstances or polluted and warm circumstances, the
258 kinetically simulated $J_{1.4}$ could be well reproduced by parameterized pseudo-steady-state $J_{1.4}$. Actually, τ vary greatly with
259 CoagS and γ, and would be higher on cleaner and colder days, while even in extremely clean and cold days with $CS = 0.0001$
260 s⁻¹ and $T = 255$ K, τ of A_3B_3 (longer than other clusters) is only ~20 min, shorter than the data collection time interval of 30
261 min. Thus for circumstances where there are high atmospheric concentrations of DMA and SA, such as most typical polluted
262 regions, we conclude that nucleation processes are rapid enough that kinetic $J_{1.4}$ can be represented by pseudo-steady-state $J_{1.4}$.

263 Figure 1 presents the comparisons between parameterized $J_{1.4}$ in this study and those simulated in the kinetic models (hereafter
264 referred to as KM) presented by Cai et al. (2021) and the cluster dynamic simulations containing all A_mB_n (m, n≤4) clusters
265 (hereafter referred to as CDS). Generally, there are good consistencies the simulated $J_{1.4}$ between KM and the parameterization
266 with the correlation coefficient (R^2) and normalized mean bias (NMB) of 0.9297 and 0.16, respectively. The simulated $J_{1.4}$ in
267 KM can be reproduced by parameterized $J_{1.4}$ within a ±50% range for most of the cases in urban Beijing, with no systematic
268 deviations found between them.

269 Figure 1b shows that for most of the circumstances, deviations between the parameterized $J_{1.4}$ and $J_{1.4}$ simulated in CDS are

270 within a range of 1 order of magnitude. The R^2 and NMB of the simulated $J_{1.4}$ between this parameterization and CDS are

271 0.7244 and 0.29, respectively. However, for circumstances with high temperatures, the parameterized $J_{1.4}$ were higher than

272 those simulated in CDS, which might be due to that the A_kB_k (k=2,3 and 4) clusters are assumed to be non-evaporative in KM

273 while they would evaporate back in CDS under high temperatures. The reasonability of cluster stability assumptions under

274 high temperatures relies mainly on the accuracy of quantum chemistry calculations, which requires more experimental

275 evidence and discussions. Additionally, due to the negative dependence of simulated $J_{1.4}$ on T, the simulated $J_{1.4}$ in this

276 parameterization were mostly lower than 10 cm^{-3}s^{-1} under temperatures higher than 15 ℃, lower than the median and mean

277 value of particle formation rates measured during long-term observations in Beijing (Deng et al., 2021). Although they are

278 relatively higher than those simulated in CDS, the simulation results of NPF occurrence did not show large deviations.

279 The computational costs of these three simulations have also been tested on the same personal computer with a Matlab program.

280 To achieve the steady-state $J_{1.4}$ in a specific atmospheric condition, the CDS and KM needs ~10 s and ~0.05 s CPU time,

281 respectively, while the calculation of parameterized pseudo-steady-state $J_{1.4}$ merely costs ~2×10^{-7} s CPU time. The CPU time

282 was reduced by a factor of 5×10^7 and 4×10^4 compared to CDS and KM, respectively. Thus introducing this parameterization

283 into 3-D chemical transport models could greatly reduce the computational costs.

284 **3.2 The Dependence of Parameterized $J_{1.4}$ on Input Parameters**

285 The correlation between parameterized SA-DMA nucleation $J_{1.4}$ and the input parameters are shown in Fig. 2. The parameters

286 involved are T, CS, [DMA], and [SA$_{tot}$]. The mean values of measured data during the observation period (281K, 0.02 s^{-1}, 3

287 ppt, and 3.5×10^6 cm^{-3}, respectively) are applied as typical conditions in the base case. Different from the semi-empirical power-

288 law functions only based on precursor concentrations presented by Dunne et al. (2016), the dependences of particle formation

289 rates on T and CS are represented in our parameterizations. With T increasing from -10 to 20 ℃, γ would increase by ~2 orders

290 of magnitude, as shown in Fig. 2a, and thus $J_{1.4}$ would decrease by over 2 orders of magnitude. This should be attributed to

291 the positive dependence of evaporation rates of A_1B_1 clusters on the temperature. Under circumstances with high tempratures,

292 the formation of A_1B_1 and subsequent formation of larger clusters and 1.4 nm particles would be suppressed. The decreasing

293 trend of observed NPF rate ($J_{1.5}$ in this case) as a function of increasing T in urban Beijing has also been reported (Deng et al.,

294 2020), consistent with our parameterizations.

295 Fig. 2b shows that $J_{1.4}$ would decrease by 2-4 orders of magnitude with CS increasing by a factor of 10, and the logarithm

296 dependence is higher in circumstances with higher CS, such as urban Beijing, where CoagS dominates the sinks. This is

297 consistent with the negative CS dependence of measured particle formation rates and NPF occurrence demonstrated in previous

298 observations in Beijing (Deng et al., 2021; Cai et al., 2021b; Cai et al., 2021a). Note that the dependence of parameterized $J_{1.4}$

299 on CS is also sensitive to T due to the synergistic effect of evaporation and coagulation on the sink of A_1B_1 clusters, which are

300 the key species in SA-DMA nucleation (Cai et al., 2022). If temperatures are higher, evaporation would be the dominant sink

301 of A_1B_1 clusters while CS only suppresses the formation of larger clusters. While under lower temperatures, such as in

302 wintertime Beijing, CS would be the dominant sink of both A_1B_1 clusters and larger clusters.

303 The parameterized $J_{1.4}$ shows an increasing trend with increasing concentrations of SA and DMA. The parameterized $J_{1.4}$ is

304 approximately proportional to [SA]^4. This high dependence of parameterized $J_{1.4}$ on [SA] could well reproduce the

305 phenomenon that rapid formation of new particles usually occurs at noon, when there is usually strong formation of SA

306 molecules in the atmosphere. The dependence of $J_{1.4}$ on [DMA] is decreasing with increasing [DMA]. This is due to the near-

307 saturation formation of A_1B_1 clusters, which is also found in kinetic model simulation results (Cai et al., 2021d). Generally,

308 the parameterization could reproduce the fact that SA-DMA nucleation is driven by SA-DMA cluster formation, dominantly

309 suppressed by cluster evaporation and coagulation sinks.

3.3 Comparison of 3D Model Simulations with Observations

As [DMA], [SA] and CS are key input variables for the $J_{1.4}$ parameterization, we first compare simulated [DMA], [SA] and CS from the DMA1.4_Mech8 scenario with observations (Fig. 3). Generally, there are good consistencies of both mean values and temporal variations, although there are still deviations at certain times. The mean simulated [DMA], [SA], and CS are 1.9 ppt, 1.4×10^6 cm^{-3}, and 0.040 s^{-1}, respectively, close to observed values of 2.0 ppt, 1.6×10^6 cm^{-3}, and 0.043 s^{-1}. In a quantitative view, the R^2 between simulated and observed [DMA], [SA], and CS are 0.04, 0.37, and 0.40, respectively, while the coefficients during NPF periods increase to 0.12, 0.51, and 0.49. The normalized mean biases (NMBs) between simulated and observed [DMA], [SA], and CS are 4.5×10^{-3}, -0.22, and -0.36, respectively, while NMBs during NPF periods are -0.40, 0.01, and -0.66. Generally, the simulation of SA concentrations is good, especially during NPF periods with intense nucleation. We note that the correlation between simulated and observed DMA concentration is lower, which may be attributed to the large uncertainty of the diurnal variation of amine emission. Nevertheless, during NPF periods, the differences between the observed DMA concentration (0.78±0.60 ppt) and our simulation (1.10±0.60 ppt) is relatively small. For [SA] and CS, to which $J_{1.4}$ are most sensitive, we compare the timeseries of simulated and observed [SA]^4/CS^2 (based on the approximate dependence of $J_{1.4}$ on [SA] and CS, as shown in Fig. 2)during NPF periods to show the deviations of the combination of these two input parameters (Fig. S6). Generally, in most nucleation events, the simulated values would not deviate from the observed values by over an order of magnitude. This indicates the validity of the comprehensive representation of input parameters in the model.

The time series of PNSDs for different simulation scenarios are presented in Fig. 4. When SA-DMA nucleation is considered, the typical PNSDs shape in observed NPF days (12/07, 12/08, 12/09, 01/20, and 01/21), characterized as the burst of nanometer-sized particles and subsequent growth, are well captured by our "best-case" scenario DMA1.4_Mech8 and also DMA1.7_Mech8. By contrast, the scenarios without DMA-SA nucleation, NoDMA_Mech7 and NoDMA_Mech0, cannot reproduce the observed NPF events with a "vacancy band" for 1~10 nm size range over the entire simulation period. Actually, although there are slightly higher sub-3 nm particle concentrations in NoDMA_Mech7 than those in NoDMA_Mech0, which are generated from the 7 nucleation pathways other than DMA-SA nucleation, the newly formed particle concentrations are too low to survive in the subsequent growth and be separated from background aerosols in the PNSDs. These results demonstrate that SA-DMA nucleation should be the dominant mechanism during NPF events in Beijing compared with other 7 mechanisms.

Our results also reproduce the dependence of NPF occurrence on CS in Beijing. As shown in Fig. S2 in the *SI*, NPF generally occurs at low CS while high CS results in too low nucleation rates to initiate NPF. The results were also validated through comparison between the timeseries of the simulated and observed CS (Fig. 3c). Note that the simulated sub-3 nm particle concentrations also increase slightly on some non-NPF days in DMA1.4_Mech8 and DMA1.7_Mech8 scenarios, however, the concentrations are ~1 order of magnitude lower than those on NPF days and the newly formed particles also fail to survive in the subsequent growth. The improvements of using the nucleation parameterization in this study is further stressed in the comparison between DMA1.4_Mech8 scenario and the scenario (CLOUD) using the parameterization from Dunne et al. (2016). Figure S3 has shown that almost no rapid nucleation processes and NPF events are found in the simulation of CLOUD scenarios. In addition to the underestimation of nucleation rates, the simulated high nucleation rates usually occur on observed non-NPF days (Fig.S7), which should be attributed to the ignorance of CS dependence in the power-law function parameterizations.

Figure 5 further compares the simulated and observed PNSDs averaged over the simulation period. The "best-case" scenario DMA1.4_Mech8 brings the averaged PNSD in 1~200 nm size range much closer to the observation than those of "base-case" NoDMA_Mech7, and the latter only shows a minor change compared to scenario NoDMA_Mech0 without any nucleation. One may notice that the averaged PNSD in 2~10 nm size range for scenario DMA1.4_Mech8 is still lower than that of observation by ~1 order of magnitude, despite the good agreement in number concentrations of particles of ~1.4 nm. This

352 could be attributed to two possible reasons: the model underestimates the actual nucleation rates; or newly formed particles of

353 ~1.4 nm grow too fast to larger size bins in the model (> 10 nm). The first one can be excluded by a generally good agreement

354 between simulated nucleation rates and ones derived from observation, even with a slightly higher mean value for the former

355 (shown in next section, Fig. 6). The observation-simulation comparison of averaged PNSDs is further conducted for individual

356 NPF days. As shown in Fig. S8, the simulated PNSDs on all NPF days follow a similar pattern as the two-month-averaged one

357 in Fig. 6, indicating that nucleation in each simulated NPF day is accompanied by subsequent rapid growth. The difference in

358 the concentration of 2-10 nm particles between observation and simulation is therefore a common feature on various days and

359 is probably attributed to the simplified assumption in particle growth simulation. Hence, the gap in 2~10 nm size range might

360 be attributed to the particle growth simulations in the model which deserves further improvement. Moreover, in spite of similar

361 performance in improving PNSDs simulations compared to the "best-case" DMA1.4_Mech8, the scenario of DMA1.7_Mech8

362 presents a shifted PNSD pattern to larger size range. For these two scenarios including SA-DMA nucleation, scenario

363 DMA1.4_Mech8 is more reasonable since a systematic underestimation exists over the entire 1~10 nm range in scenario

364 DMA1.7_Mech8. Still, the conversion from 1.4 nm rate to those for larger particles through modified Kerminen-Kulmala

365 equation is an alternative way to depict SA-DMA nucleation for other models with different aerosol size settings.Overall,

366 despite aforementioned deficiencies, our updated WRF-Chem/R2D-VBS model configured with the SA-DMA nucleation

367 parameterization shows substantial improvement in representation of NPF events and the PNSD.

368 **3.4 Contribution from Various Pathways to Nucleation Rates and Particle Number Concentrations**

369 Quantitative analysis over various nucleation pathways is performed here to improve the understanding of NPF in Beijing. As

370 presented in Fig. 6, the variation of nucleation rates, which are derived from observed PNSD data, is well represented by the

371 best-case scenario DMA1.4_Mech8. Compared to the vast majority contribution from SA-DMA nucleation, the nucleation

372 rates from other nucleation mechanisms are lower by a factor of ~100. In addition, SA-DMA nucleation contributes over 60%

373 to aerosol population, reinforcing its dominant role in modulating aerosol population in urban atmospheres.

374 **3.5 Sensitivity Analysis**

375 Having shown the significant improvement of model performance in simulating NPF by coupling the SA-DMA nucleation

376 parameterization, we acknowledge that the simulation of SA-DMA nucleation in 3D model still has uncertainties in terms of

377 both source-sink representation of DMA and nucleation parameterization. Here, several key factors which may alter model

378 performance were selected to perform sensitivity analysis.

379 First, the uncertainties brought by ΔG achieved from different quantum chemistry results are tested for both parameterized $J_{1.4}$

380 and the 3-D chemical transport model simulations. In previous studies, a number of ΔG values have been reported: -11.02

381 kcal mol^{-1} (Ge et al., 2020b), -15.40 kcal mol^{-1} (Ortega et al., 2012), -13.54 kcal mol^{-1} (Myllys et al., 2019). The ΔG of -14.00

382 kcal mol^{-1} was applied in (Cai et al., 2021d) to achieve good consistencies between simulated and measured $J_{1.4}$ is also applied

383 in the sensitivity analysis. Figure S9 shows the variation of parameterized $J_{1.4}$ applying different ΔG values at 281 K, the

384 median temperature of the observation period. For DMA with median values of ~3 ppt, different $J_{1.4}$ could vary by ~5 orders

385 of magnitude with ΔG between -11.02 kcal mol^{-1} and -15.40 kcal mol^{-1}, while $J_{1.4}$ with ΔG of -13.54 kcal mol^{-1} is also lower

386 than that of -15.40 kcal mol^{-1} by a factor of ~10. However, if the DMA concentrations are up to ~30 ppt, the differences of $J_{1.4}$

387 when ΔG varies between -13.54 kcal mol^{-1} and -15.40 kcal mol^{-1} would become much smaller, due to the saturated formation

388 of A_1B_1 clusters. For the temperature of 298.15 K, the sensitivities of parameterized $J_{1.4}$ are relatively larger, because the

389 formation of A_1B_1 clusters is far from saturation. Generally, the parameterized $J_{1.4}$ could be very sensitive to different ΔG

390 values achieved from quantum chemistry results due to the essential influence of cluster stabilities. As a result, using a lower

391 ΔG value of -15.40 kcal mol^{-1} in the 3-D simulations with the DMA1.4_Mech8 scenario configuration could lead to much

392 higher nucleation rates compared to the observation (Fig. S10). Thus we call for a more systematic performance assessment

393 of quantum chemistry calculation methods to constrain the uncertainties of cluster thermodynamic stabilities.

394 Moreover, for the DMA source, we conduct two sensitivity scenarios of doubling (DMA2) and halving (DMA0.5) the inputted

395 DMA emission to test the influence of limited measurements in constraining the DMA/NH_3 emission ratio. As for the three

396 sink processes, the parameters for DMA-•OH reaction and wet deposition reported in the literature have relatively small

397 differences while aerosol uptake coefficient of DMA covers a wide range over two orders of magnitude. We then conduct two

398 sensitivity scenarios using the upper (4.4×10^{-2}, Upt4.4E-2) and lower (5.9×10^{-4}, Upt5.9E-4) limit of aerosol uptake coefficient.

399 All sensitivity scenarios are on the basis of the DMA1.4_Mech8 configuration. The influence of scaled DMA emissions and

400 varying uptake coefficients on simulated DMA concentration, PNSDs, and nucleation rate is shown in Fig. S11-S21 in the *SI*.

401 As expected, the DMA concentration, especially for the nighttime spikes, is sensitive to the emission change. In DMA0.5, the

402 simulated J are lower than those observed in almost all cases. In contrast, although the simulated J in DMA2 is on average

403 higher than observations, they are comparable in some specific cases. Considering that during NPF cases, the observed [DMA]

404 are averagely 1.4 times higher than those simulated in DMA1.4_Mech8, we propose that the slight underestimation of DMA

405 concentrations in this case might be the reason for underestimation in J in some cases. The sensitivity analysis for the uptake

406 coefficient, however, shows different results. A higher uptake coefficient of 4.4×10^{-2} leads to a much lower DMA

407 concentration (10% of the "best-case") while DMA concentration only increase slightly when the lower limit of 5.9×10^{-4} is

408 used. Moreover, the change in uptake coefficient show limited effect on PNSD. The reason is that the DMA concentrations

409 during NPF periods are much less affected by the changes in uptake coefficient than those in non-NPF periods, since NPF

410 usually occurs at low CS conditions when the uptake of DMA is weak.

411 The sensitivity analysis above show that the parameters used in our simulation are reasonable, since perturbations within the

412 ranges reported in the literature generally worsen the model performance. We also expect more field measurements of DMA

413 emission and its aerosol uptake to further constrain the key source-sink process parameters in the simulation of DMA, although

414 some of them show minor effect on NPF and PNSD simulations.

4 Conclusions

416 This study presents a dynamic-based SA-DMA nucleation parameterization for application in 3-D chemical transport models.

417 Compared to the more widely-used semi-empirical power-law fitting parameterizations, this new parameterization is based on

418 the key pathway of SA-DMA cluster formation and includes representations of the coagulation scavenging effect and cluster

419 stability. Pseudo-steady-state assumptions were applied to reduced computational time and were validated according to the

420 short characteristic equilibrium time and through comparisons with the cluster dynamic simulations and the kinetic model.

421 Relative to simulating the SA-DMA nucleation with cluster dynamic simulations or the kinetic model, application of this new

422 parameterization in 3-D chemical transport models greatly reduces the computational costs. We incorporated this new

423 parameterization as well as the sources and sinks of DMA into the WRF-Chem/R2D-VBS model. Using the updated model,

424 we simulated the DMA concentrations and PNSDs in Beijing during December 2018 and January 2019. Comparisons were

425 made between 3-D model simulations and ambient measurements.

426 Good consistency was achieved in simulating the precursor concentrations, which validated the source-sink simulation of SA

427 and DMA. Our quantitative analysis showed that compared to other nucleation mechanisms, SA-DMA nucleation contributed

428 to >99% of particle formation rates and >60% of particle number concentrations during the simulation period in urban Beijing.

429 Although the uncertainties exist due to the excess rapid growth in the 3-D simulations, SA-DMA nucleation should be a

430 dominant sources of aerosol populations due to the dominant contribution to new particle formation rates. Further, the 3-D

431 simulations with the new parameterization predicted the CS-dependent NPF occurrence in urban Beijing and quantitatively

432 reproduced the particle size distributions. These results demonstrated that incorporating the SA-DMA nucleation
433 parameterization, including the effect of coagulation scavenging and cluster stabilities, with 3-D chemical transport models
434 can significantly improve the simulation of NPF and the particle size distributions.

435 Our results demonstrated that 3-D simulations with a new SA-DMA parameterization could reproduce the CS-dependent
436 particle formation rates and NPF occurrence observed in Beijing. Given that CS varies widely between NPF days and non-
437 NPF days in urban atmospheres (Xiao et al., 2015; Wu et al., 2007; Deng et al., 2021), compared to semi-empirical power-law
438 functions, this parameterization of particle formation rates is likely more effective in predicting the NPF occurrence in urban
439 atmospheres. Additionally, the particle formation rates from other nucleation mechanisms should also be suppressed by high
440 CS, which needs further exploration and parameterizations. Our methodology of applying pseudo-steady-state assumptions to
441 kinetic models could be important in reducing computational costs of other SA-amine nucleation systems. For instance,
442 quantum chemistry calculations indicate that other basic molecules like trimethylamine and diamines (Jen et al., 2016; Jen et
443 al., 2014a), might also form relative stable clusters with SA molecules, hence the methodology of parameterizations in this
444 study could be extended for them, or the basic molecules could also be treated as equivalent DMA concentrations. The
445 improvements in model simulations of particle size distributions are important for improving simulations of cloud
446 condensation nuclei and the climate effects of aerosols and NPF events. The improvements also provide more evidence for
447 quantitatively evaluating the environmental and health effect of newly-formed particles.

448

449 Codes/Data availability

450 The simulation output data and codes needed for figure reproduction have been posted on Github. The link is
451 https://github.com/laoyeyelao/new-SA-DMA-parameterization.git.

452 Author Contribution

453 Y.L., J.S., B.Z., and J.J. designed the research; J.Z., M.K., and J.J. collected the observational data; Y.L., R.C., and J.J. set up
454 and tested the parameterization; J.S., B.Z., S.W., and D.G. developed the 3-D model and performed the simulations; Y.L. and
455 J.S. analyzed the data with the help of R.C., B.Z., and J.J.; M.S. and Y.G. presented important suggestions for the writings;
456 Y.L., J.S., B.Z., and J.J. wrote the paper with inputs from all co-authors.

457 Competing Interests

458 Some authors are members of the editorial board of journal *Atmospheric Chemistry and Physics*. The peer-review process was
459 guided by an independent editor, and the authors have also no other competing interests to declare.

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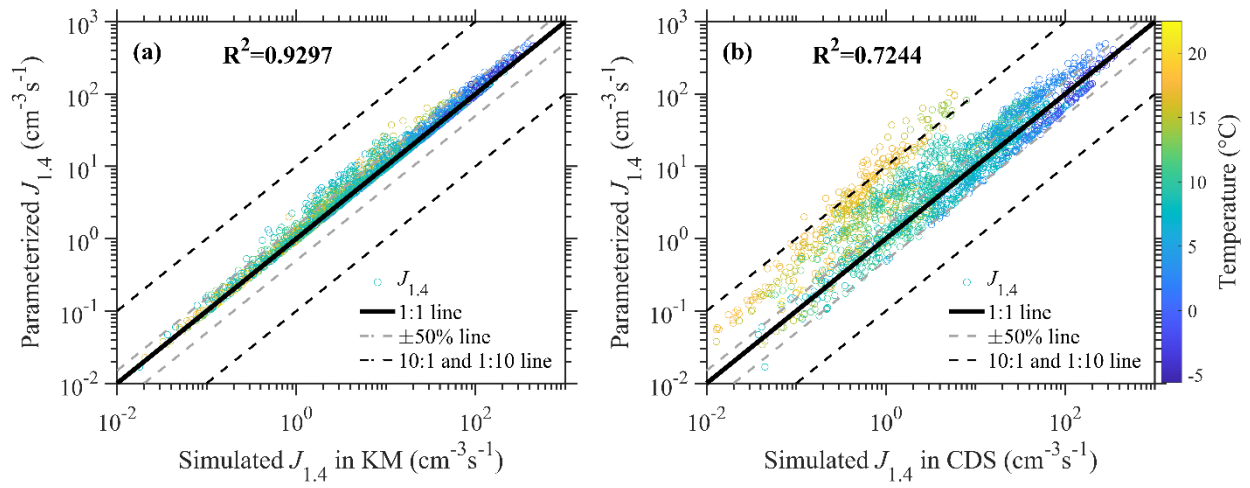
Figure 1. $J_{1.4}$ **Comparison of simplified parameterization method with kinetic model (KM) results (a) and cluster dynamic simulation (CDS) results (b).** The red hollow circles showed the simulation results according to atmospheric observation data. The grey straight line represents the 1:1 line, while the grey dashed line represents the ±50% variation and the black dashed lines represent 1:10 or 10:1 line. The circles are colored by the temperatures.
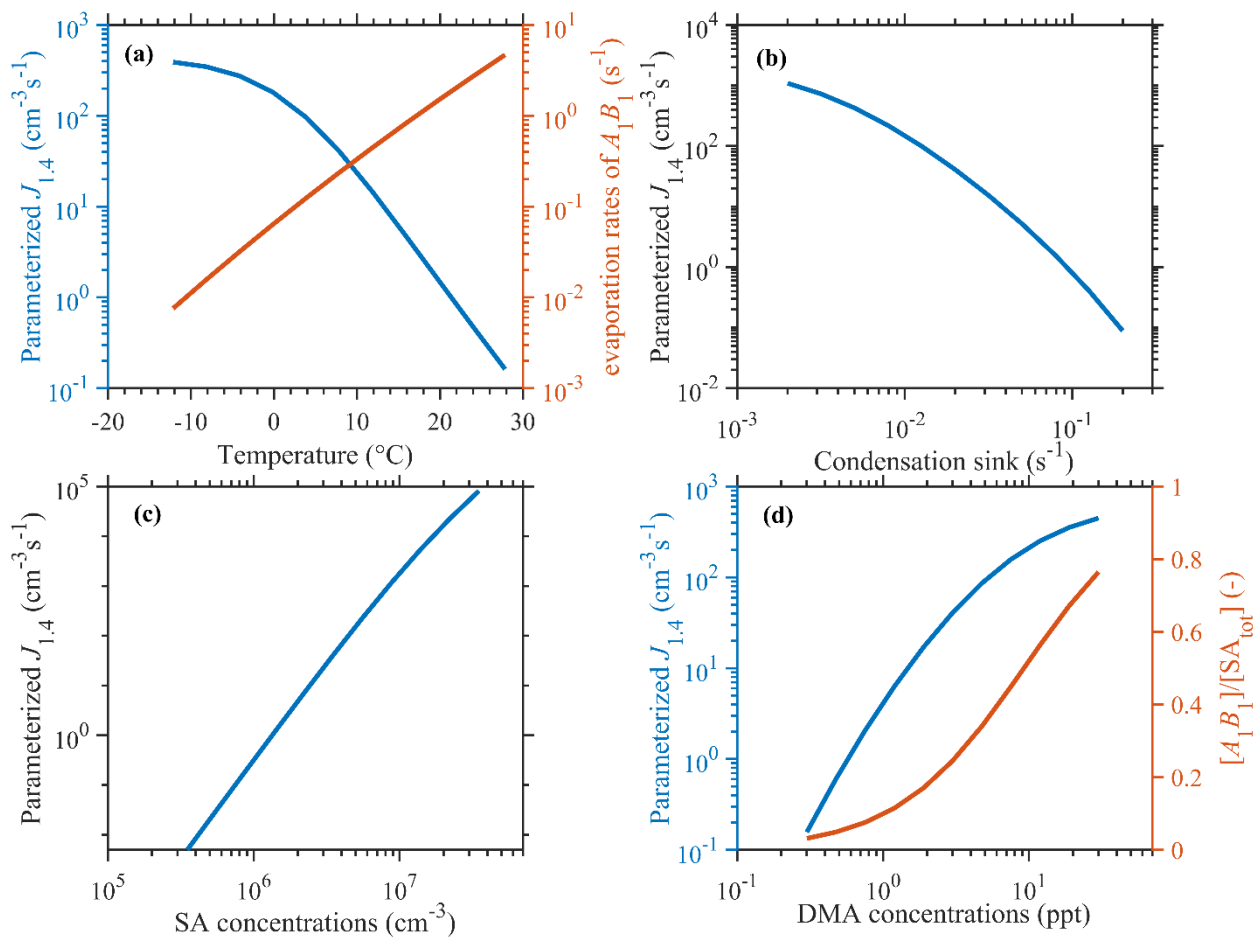
Figure 2. Dependence of simulation results on varying *T*, *CS*, [DMA], [SA]. The values of fixed parameters are 281K, 0.02 s^{-1}, 3 ppt, and 3.5$\times$10^6 cm^{-3}, respectively, as median values during NPF events in our simulation period.

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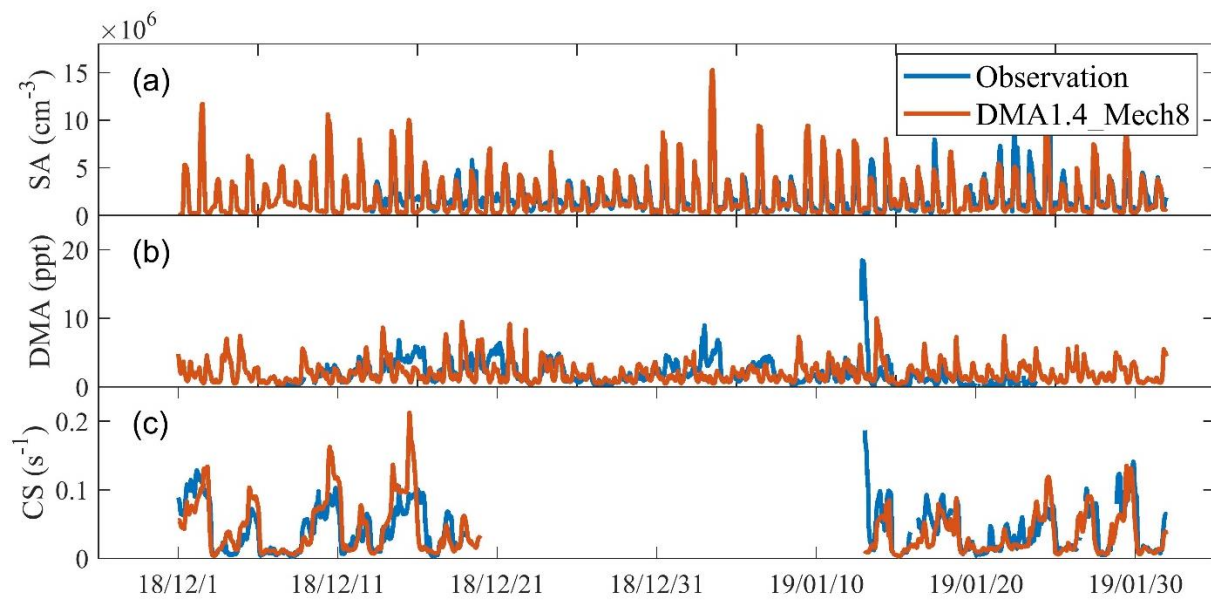
Figure 3. Comparison of simulated concentrations of DMA (a), SA (b). and CS during periods with full PNSD observation (c) with field measurements for wintertime Beijing (December 2018 and January 2019).

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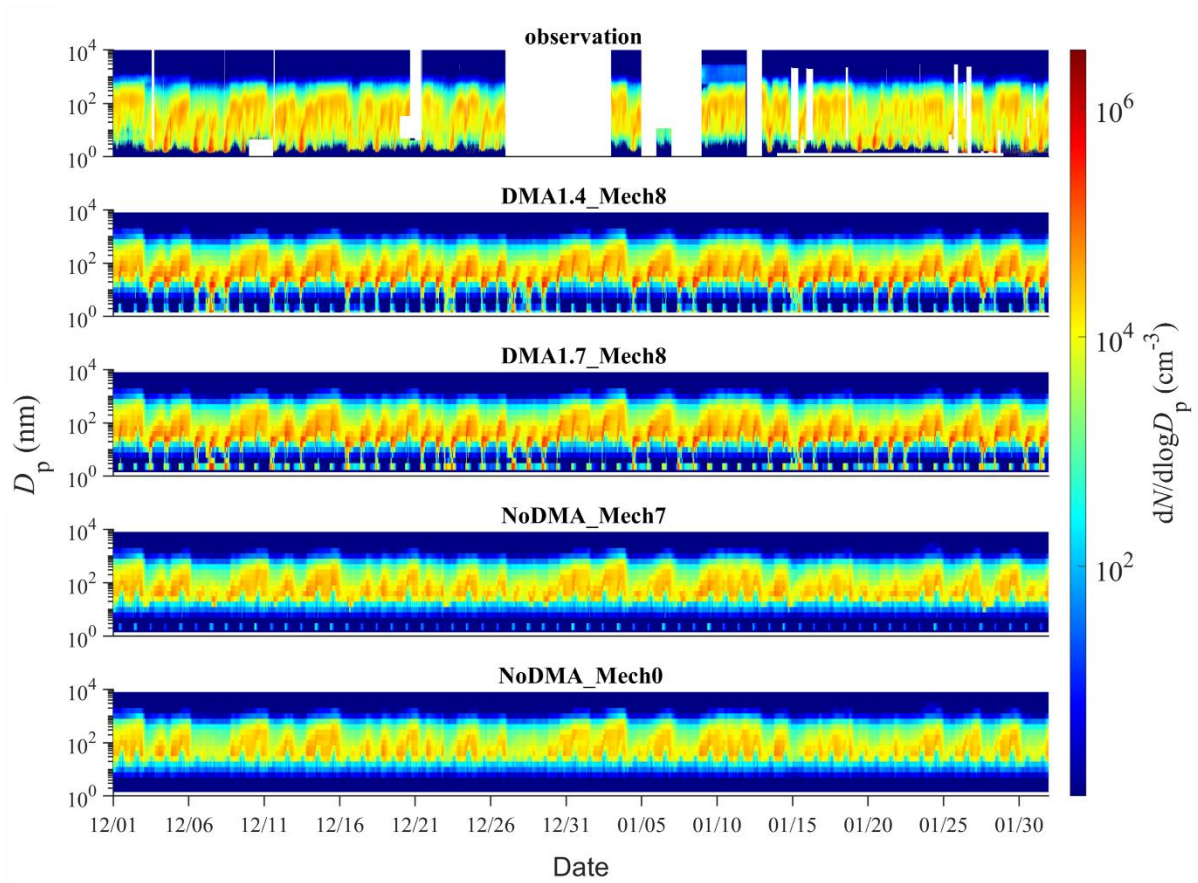
Figure 4. Comparison of time series of particle number size distribution simulated by various scenarios with the observed one. Description of four scenarios is detailed in *Configuration of the Updated WRF-Chem/R2D-VBS Model* section.

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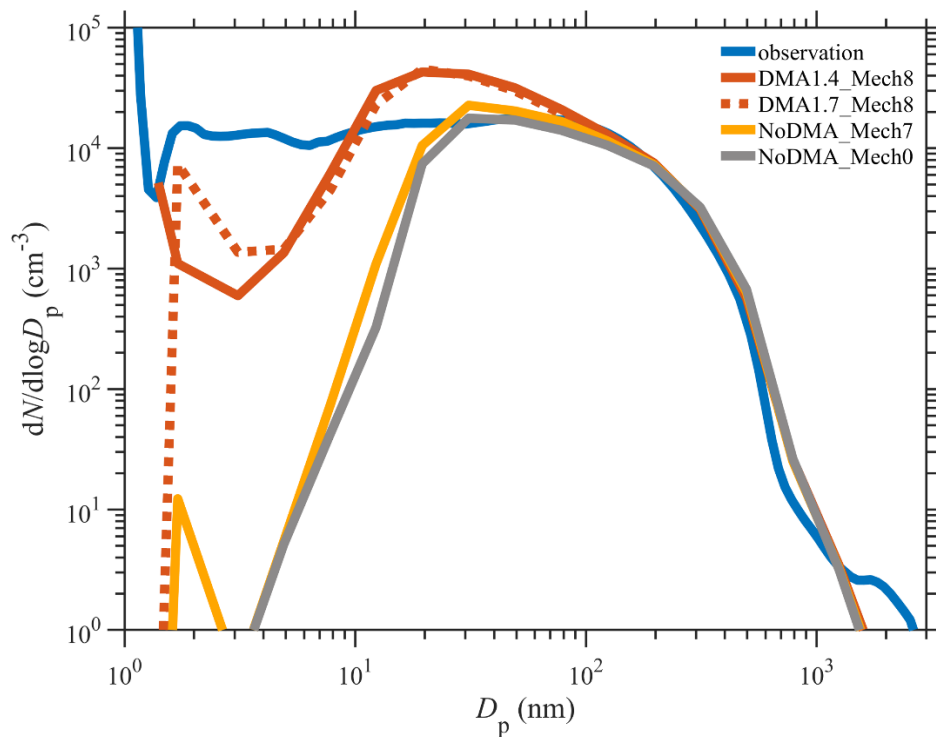
Figure 5. Comparison of averaged particle number size distribution simulated by various scenarios with the observed one. Description of four scenarios is detailed in *Configuration of the Updated WRF-Chem/R2D-VBS Model* section.
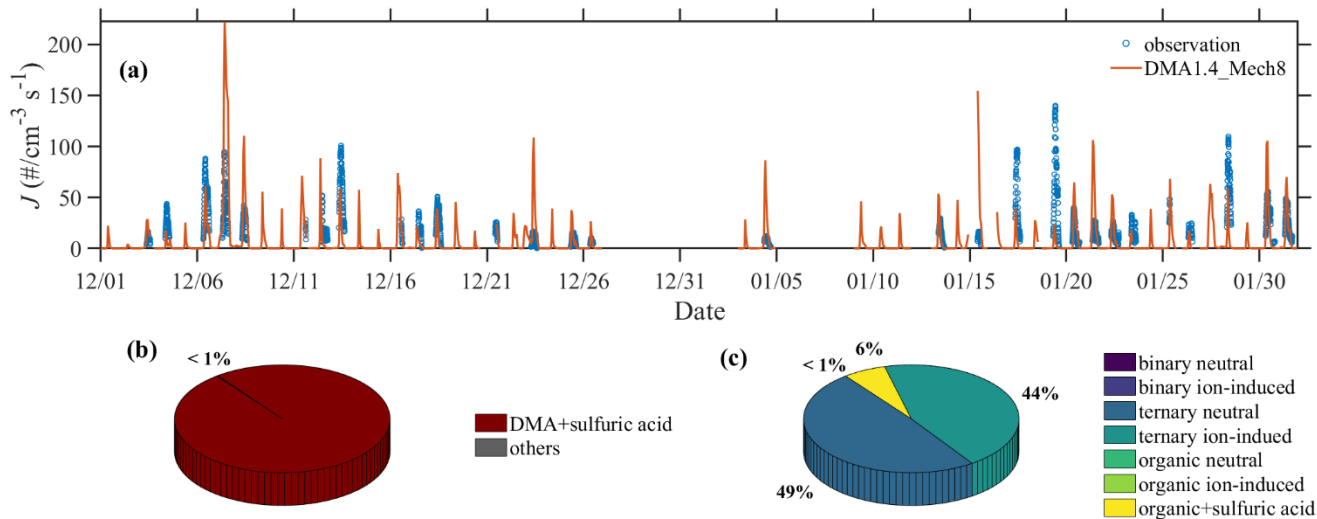
Figure 6. Comparison of simulated nucleation rates with those derived from field measurements (a), and contribution from different nucleation mechanisms (b) with a special illustration of nucleation pathways other than SA-DMA (c).