Experimental evidence for the role of ions in particle nucleation under atmospheric conditions

BY HENRIK SVENSMARK1,*, JENS OLAF P. PEDERSEN1, NIGEL D. MARSH1, MARTIN B. ENGOFF1 AND ULRIK I. UGGERHØJ1,2

1 Centre for Sun-Climate Research, Danish National Space Centre, 2100 Copenhagen, Denmark
2 Institute of Physics and Astronomy, University of Aarhus, 8000 Aarhus, Denmark

Experimental studies of aerosol nucleation in air, containing trace amounts of ozone, sulphur dioxide and water vapour at concentrations relevant for the Earth’s atmosphere, are reported. The production of new aerosol particles is found to be proportional to the negative ion density and yields nucleation rates of the order of 0.1–1 cm$^{-3}$ s$^{-1}$. This suggests that the ions are active in generating an atmospheric reservoir of small thermodynamically stable clusters, which are important for nucleation processes in the atmosphere and ultimately for cloud formation.

Keywords: cosmic rays; aerosol nucleation; clouds

1. Introduction

The role of ions in the production of aerosols is among the least understood, but potentially the most important, process in the Earth’s atmosphere. Atmospheric (Hoppel et al. 1994; Clarke et al. 1998; Birmili et al. 2003; Lee et al. 2003; Kulmala et al. 2004) and experimental (Berndt et al. 2005) observations have shown that the nucleation of aerosol particles can occur under conditions that cannot be explained by classical nucleation theory. Several ideas have been put forward to solve this nucleation problem, e.g. ion-induced nucleation (Arnold 1980; Raes et al. 1986; Turco et al. 1998) and ternary nucleation (Kulmala et al. 2000). However, experimental investigations exploring the role of ions in particle production are scarce and often at conditions far removed from those relevant for the lower part of the atmosphere (Bricard et al. 1968; Vohra et al. 1984; Kim et al. 2002; Nagato et al. 2005; Wilhelm et al. 2003). Here, we show that the production of new aerosol particles is proportional to the negative ion density under experimental conditions similar to those found in the lower troposphere over oceans. Since production rates at 3 nm were observed to be 1–10 cm$^{-3}$ s$^{-1}$, and numerical simulations yielded nucleation rates of initial stable clusters (approx. 1 nm) around 0.1–1 cm$^{-3}$ s$^{-1}$, it is suggested that ions

* Author for correspondence (hsv@spacecenter.dk).
are active in continuously generating a reservoir of small thermodynamically stable clusters that can then rapidly grow in the presence of condensable vapours. These results demonstrate that ions probably play an important role in the production of new aerosol particles in the Earth’s atmosphere.

2. Experimental procedure

The measurements were performed in a 7 m$^3$ reaction chamber, which was continuously flushed with purified air at 30.5 l min$^{-1}$ at standard temperature and pressure (STP). Variable concentrations of water vapour (H$_2$O), ozone (O$_3$) and sulphur dioxide (SO$_2$) could be added to the chamber, which is shown schematically in figure 1. Five walls of the chamber were constructed from mylar with the final wall constructed from Teflon to allow for the transmission of UV light. Air was obtained via an inlet situated externally to the building housing the experiment. The air was compressed and dried with an oil-free compressor and then passed through a series of filters, including active charcoal, a molecular sieve, citric acid and both 10 and 3 nm particle filters. The air finally entered the experiment via a tube inserted about half a meter into the chamber.

H$_2$O was introduced by circulating deionized water through a GoreTex tube inserted into the air flow, which allowed the relative humidity to vary over the range 2–90%. SO$_2$ was added as a 5 p.p.m. mixture of SO$_2$ in dry air (Air Liquide) and O$_3$ was introduced by directing a fraction of the flow (0.5 l min$^{-1}$ STP) through an ozone generator. Both the flows containing SO$_2$ and O$_3$ were passed through the 3 nm particle filters before mixing with the main air flow at the entrance to the chamber. At all times during the experiments, the concentrations of H$_2$O, SO$_2$ and O$_3$ were maintained at constant levels. Teflon tubing was used everywhere, except for a stainless steel section between the

Figure 1. The reaction chamber. 1, the chamber; 2, UV array; 3, honeycomb collimator; 4, air inlet; 5, ozone line; 6, SO$_2$ line; 7, gas and aerosol outlet; 8, electrodes.
compressor and the chamber’s gas system. The pressure in the chamber was held a few Pascals above the atmospheric pressure and a stable room temperature was maintained by the laboratory air-conditioning system (296 ± 1 K). All flow outlets, used for measurements of particles and gases extended into the chamber to avoid possible artefacts from wall effects.

UV radiation, primarily at 253.7 nm, was provided by an array of seven mercury discharge lamps mounted so that they illuminated the chamber through the wall constructed from Teflon. The radiation was collimated via an 80 mm thick, honeycomb wall (1/4 in. pore size) mounted outside the chamber and coated with an UV-resistant matt black paint. The UV initiates a photochemical reaction where O_3 is photolysed to produce OH-radicals and through a series of reactions, involving SO_2, O_2 and H_2O, produces sulphuric acid (H_2SO_4). The resulting H_2SO_4 concentration was estimated using the empirical relation between aerosol growth rate and sulphuric acid concentration given by Kulmala et al. (2001). The UV intensity was mapped out over approximately a quarter of the chamber with a total of ca 21 000 measurement points across the front, middle and back of the chamber with 1 cm resolution. This ensured that the UV field was homogeneous.

Temperature, pressure and relative humidity were measured at the front wall of the chamber, the main inlet and the humidifier. Temperature was additionally measured at the top and bottom mid-points of the chamber. The O_3 and SO_2 concentrations were monitored using trace gas analysers, which were sensitive down to 0.1 p.p.b. for O_3 (Teledyne model 400A) and 0.05 p.p.b. for SO_2 (Thermo model 43 CTL). The rough composition of the gas mixture in the chamber could also be analysed using a Pfeiffer Quadrupole QMG 422 mass spectrometer.

The ions were produced in the chamber by the naturally occurring galactic cosmic radiation and the decay of the natural abundance of radon (monitored with a Durridge RAD7 instrument). In addition to this, the average production of ions could be enhanced to ionization levels relevant for the atmosphere (1–60 ion pairs cm\(^{-3}\) s\(^{-1}\)), with two 35 MBq Cs-137 gamma sources, placed on either side of the chamber at a distance that ensured the entire chamber was radiated with the additional ionization. It was also possible to reduce the number of ions via an electric ‘clearing’ field (0–12 000 V m\(^{-1}\)). This was achieved by applying a voltage drop across two acid proof stainless steel plates (1.7×1.7 m\(^2\)) mounted within the chamber on the opposing walls. The field strength could be varied over a range of voltages corresponding to ion lifetimes of ca 1–200 s.

The ion current in the chamber was monitored using a Gerden (Gerdien 1905; Aplin & Harrison 2000) type ion detector mounted on the front wall of the chamber. The detector consists of a cylindrical aluminium tube of length 25.8 cm and inner radius 1.25 cm (outer electrode), with a coaxial thin metal rod suspended at its centre (inner electrode). Air from the chamber flowed through the tube at a rate of ca 9 l min\(^{-1}\). By applying a positive (negative) potential across the electrodes, negative (positive) ions were forced to move towards the central electrode causing a current to flow. This current was measured by a Keithley Model 6514 electrometer. No significant difference was found between the total concentrations of positive and negative ions with mobilities greater than 1 cm\(^2\) V\(^{-1}\) per second.
Varying the field strength within the tube controls, the minimum mobility of the ions contributing to the measured current and thus a spectrum of ion mobilities can be obtained. The spectra, obtained over the full range of experimental conditions reported here, indicate that the majority of small ions possess a mobility, $\mu \sim 1 \text{ cm}^2 \text{ V}^{-1} \text{ per second}$. The small ion density in the reaction chamber was then estimated from the current, $I$, that was measured when the potential across the electrodes was fixed at 1.23 V. This limits the small ions collected to those having a minimum mobility of approximately $1 \text{ cm}^2 \text{ V}^{-1} \text{ per second}$. The mobility cut-off is not sharply defined since ions with lower mobilities will still be collected on the central electrode if they enter the Gerdien tube near this electrode. The contribution of these ions to the current measurement can, however, be estimated from the instrument response function. Using the results from Tammet (1995), the minimum ion mobility was then converted into a maximum ion diameter of approximately 1 nm. Finally, the ion density, $n_e$, was obtained from $n_e(\mu > 1 \text{ cm}^2 \text{ V}^{-1} \text{ per second}) = I/(e \times f)$, where $e$ is the charge per ion and $f$ is the rate of flow through the tube. A result of this procedure is that larger ions or ionized aerosols potentially contribute to the extracted ion density, but the mobility spectra suggest that their contribution is negligible.

The number of aerosols present in the chamber was measured with a TSI Ultra Fine Condensation Particle Counter (model 3025A) capable of measuring particles in the range of 3–150 nm.

The gas mixture in the reaction chamber during all of the experiments resembles those found in the lower troposphere over the oceans, i.e. O$_3$ (approx. 25 p.p.b.), H$_2$O (approx. 35% relative humidity) and SO$_2$ (80–230 p.p.t.) (Seinfeld & Pandis 1998, p. 61 & 96).

### 3. Burst and steady-state experiments

Two types of experiments were performed: (i) a ‘burst’ of H$_2$SO$_4$ was produced from a short exposure to the UV light, and (ii) steady-state conditions of H$_2$SO$_4$ were achieved under continuous exposure to the UV light.

In the burst experiment, the chamber was exposed to a 10 min illumination of UV light resulting in the rapid production of sulphuric acid that reached a peak concentration around $4 \times 10^7 \text{ cm}^{-3}$. This is well below the limit of homogeneous nucleation, which is around $10^9 \text{ cm}^{-3}$ (Seinfeld & Pandis 1998, p. 578). The peak concentration lasted for a few minutes before decaying exponentially owing to losses to the walls of the reaction chamber. Figure 2b shows the typical response of particles larger than 3 nm, where an initial steep rise in aerosol number to a maximum is followed by a slow decay lagging the H$_2$SO$_4$ concentration. Clearly, the system possesses some very long transients requiring typically 4 h before returning to initial conditions and allowing the cycle to be repeated with another burst of UV light. The average number of particles with diameter greater than 3 nm captured by the TSI particle counter, $N(d>3 \text{ nm})$, over each 4 h cycle was found to be proportional to the small ion (with $>1 \text{ cm}^2 \text{ V}^{-1} \text{ per second}$) density in the chamber (figure 2a).
The aerosol response to different ion densities can also be characterized by the time it takes from the initial UV exposure until the first particles begin to appear at 3 nm (figure 3b). This time-interval is referred to here as the delay time, \( t \) (figure 3b) and is the time it takes for the aerosol concentration greater than 3 nm to reach a threshold of 10 cm\(^{-3}\). The observed delay times also show a dependence on the ion density, with the lowest ion densities yielding a delay time of around 11 min, which decreases to about 6 min at higher ion densities (figure 3b). Relaxation to steady state under continuous exposure to UV light typically took ca 8 h and resulted in a constant concentration of H\(_2\)SO\(_4\) around \( 2 \times 10^8 \) cm\(^{-3}\). Figure 4a shows the number of particles larger than 3 nm obtained under steady-state conditions as a function of the observed ion-current. The typical response of the steady state \( N(d>3 \text{ nm}) \) under various ionization levels in the chamber can be seen in figure 4b. These measurements further demonstrate that the particle production depends on the ion density.

The aerosol response to different ion densities can also be characterized by the time it takes from the initial UV exposure until the first particles begin to appear at 3 nm (figure 3b). This time-interval is referred to here as the delay time, \( \tau \) (figure 3b) and is the time it takes for the aerosol concentration greater than 3 nm to reach a threshold of 10 cm\(^{-3}\). The observed delay times also show a dependence on the ion density, with the lowest ion densities yielding a delay time of around 11 min, which decreases to about 6 min at higher ion densities (figure 3b). Relaxation to steady state under continuous exposure to UV light typically took ca 8 h and resulted in a constant concentration of H\(_2\)SO\(_4\) around \( 2 \times 10^8 \) cm\(^{-3}\). Figure 4a shows the number of particles larger than 3 nm obtained under steady-state conditions as a function of the observed ion-current. The typical response of the steady state \( N(d>3 \text{ nm}) \) under various ionization levels in the chamber can be seen in figure 4b. These measurements further demonstrate that the particle production depends on the ion density.

The experimental results were tested with a mixture of argon (79%) and oxygen (21%). No significant differences were observed from those described above, which suggests that the presence of nitrogen is not crucial. This indicates that particle formation involving ions most probably occurs via negative ion chemistry, since positive ion chemistry requires the presence of nitrogen (Smith & Spangel 1996).

To exclude the possibility that the experimental results obtained were due to an impurity in the compressed air, the experiments were repeated using synthetic, dry and radon free air (Synthetic Air 5.0, Strandmøllen). No discernible differences were observed. The experiments were also performed with the purified air excluding O\(_3\).
and SO₂ alternatively. The lack of particles detected at 3 nm in both the instances showed that these trace gases were essential for the observed production, although this does not rule out that additional gases are involved in the nucleation.

### 4. Reducing ion lifetime with the electric field

Both the ‘burst’ and steady-state experiments indicate that the production of new aerosol particles is proportional to the negative ion density. At these experimental conditions, it can be concluded that ions are key to producing stable clusters. Any other mechanism which could produce particles without the involvement of ions can only have made a minor contribution to the particle production. To further investigate the time-scale to produce a charged critical cluster, an electric ‘clearing’ field has been used. Applying an electric field of, for example, 600 V m⁻¹ reduces the small ion life time to seconds, thus decreasing the time available for the ions to participate in nucleation. However, this did not have any effect on the nucleation process, and only at much larger electric field strengths did a significant response become apparent. For field strengths up to 6000 V m⁻¹, the particle production was reduced by ca 20% and at larger fields up to the current maximum of 12 000 V m⁻¹, the particle production was reduced by ca 50%. Since, as stated earlier, ions are involved in almost all particles produced, this indicates that the characteristic time for producing a stable cluster is very short, i.e. 2 s or less. The observation also indicates that the clusters become neutralized on the same time-scale as they would otherwise have been extracted from the chamber by the electric field.

In the experimental conditions reported here, classical theory suggests that the critical cluster size is of the order of 3 nm. This is based on the parametrization in Vehkamäki et al. (2002) and an estimate of the mole fraction of H₂SO₄ to be 0.2 (Seinfeld & Pandis 1998, p. 527). It would be surprising if the

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**Figure 3.** (a) Delay time, \( \tau \), as a function of ion density, \( n_e \). (b) Magnification of figure 2b (see figure 2 caption for details).
subcritical clusters could stabilize at just under 3 nm in less than 2 s and then take a further ca 10 min to grow through the 3 nm detection limit. More likely the clusters have stabilized at significantly smaller diameters and then, through coagulation, generated a distribution of thermodynamically stable clusters below the 3 nm detection limit that can rapidly grow in the presence of condensable vapours. The existence of a sub-3 nm reservoir of thermodynamically stable clusters was initially proposed by Kulmala et al. (2000). However, they suggested ternary nucleation as the source for the reservoir rather than ions as is proposed here.

5. Numerical simulations

To investigate the size of the critical cluster $k_0$ and the production rate of stable clusters $S$ under the experimental conditions, numerical simulations of particle coagulation and condensation have been compared with the experimental results. The evolution of the cluster distribution is given by (Seinfeld & Pandis 1998, p. 682)

$$\frac{dN_k}{dt} = \frac{1}{2} \sum_{j=2}^{k-1} K_{j,k-j} N_j N_{k-j} - \sum_{j=1}^{\infty} K_{k,j} N_k N_j - \lambda N_k + \beta_{k-1} N_{k-1} - \beta_k N_k + S \delta_{k,k_0},$$

(5.1)

Equation (5.1) describes the number density, $N_k$, of clusters with $k$ sulphuric acid molecules, where the equilibrium concentration of water in each cluster is reached instantaneously. The coagulation coefficient, $K_{ij} = \pi (R_i R_j)^2 (c_i^2 + c_j^2)^{1/2}$, where $c_i = (8k_B T/\pi m_i)^{1/2}$ is the mean velocity of clusters with $i$ $\text{H}_2\text{SO}_4$ molecules; $T$,
temperature; $k_B$, Boltzmann constant; and $R_i$, the radius of a cluster with $i$ H$_2$SO$_4$ molecules. The rate of sticking to the walls, $\lambda$, is approximated with a constant for all clusters and given by the observed loss rate of $N(d>3 \text{ nm})$ during the burst experiments. The $\beta_k$-term describes the condensation of H$_2$SO$_4$ molecules in the gas phase to the $k$th cluster and is given by $N_1K_{k,1}$ (Seinfeld & Pandis 1998, p. 550).

In the simulation, the resulting particle distribution after a number of hours reaches a steady state between particle losses to the walls and growth by coagulation, producing a reservoir of particles with sizes below the 3 nm experimental detection limit. Following a simulated burst of UV light, this reservoir of particles begins to grow via condensation and appear above 3 nm at the rates of 1–10 cm$^{-3}$s$^{-1}$. The resulting evolution of simulated particles with $d>3$ nm for a single burst experiment compares favourably with the experimental data (figures 2b and 3b). By varying the free parameters $k_0$ and $S$ in the model, the cumulative number of particles with $d>3$ nm is found to be dependent on both $k_0$ and $S$ (figure 5a), while the time delay is strongly dependent on $k_0$ and only weakly dependent on $S$ (figure 5b). To satisfy the constraint that $\tau>6$ min, requires $k_0 \leq 10$ H$_2$SO$_4$ molecules (figure 5b). Limiting $k_0=5$ allows for an estimate of $S$ which is found to be of the order 0.1–1 cm$^{-3}$s$^{-1}$ (figure 5a, and right-hand axis figure 2a). The simulations then reproduce a delay time similar to that observed in the experiments (figure 3a, black diamonds), and the averaged $N(d>3 \text{ nm})$ over each 4 h cycle replicates the experimental data very well (figure 2a, black diamonds). The simulations were also performed for the steady-state experiments (figure 4a, solid line) and these too compared favourably with the experimental data.

Recent calculations of particle production owing to ion-induced nucleation at conditions found in the lower troposphere over the oceans find much smaller production rates at 3 nm, e.g. less than 100 particles cm$^{-3}$ in 12 h (Lovejoy et al. 2004). In contrast, models by Yu & Turco (2001), Yu (2006) and Laakso et al. (2004) indicate much higher nucleation rates in closer agreement with our

Figure 5. Numerical simulations of the burst experiment indicating how the number of H$_2$SO$_4$ molecules in a critical cluster, $k_0$, varies with (a) 4 h integrated $N(d>3 \text{ nm})$ and (b) delay time, $\tau$. The colours in both plots refer to the production rate $S$, where 0.5, 1.0, 1.5 and 2.0 cm$^{-3}$s$^{-1}$ are represented by red, green, blue and light blue, respectively. Grey shading indicates the range of experimental data in figures 2 and 3.
results. These uncertainties in simulated nucleation rates are likely to be owing
to differences in the treatment of cluster thermodynamics in each model.

6. Discussion

The above experiments and simulations suggest that a mechanism is active involving
ions, the trace gases SO$_2$, O$_3$ and H$_2$O, all at typical levels found in the atmosphere
(Seinfeld & Pandis 1998, p. 61 & 96). With these gases present, the mechanism
apparently produces a reservoir of stable clusters, most probably containing H$_2$SO$_4$
molecules, in the absence of UV light. The observation that the negative ion
chemistry seems to be important for the nucleation process hints at the presence of an
electron as necessary for stabilizing the subcritical cluster during the initial
nucleation phase. To illustrate this idea, a possible pathway is presented below.

When energetic ionizing particles interact with the gas in the chamber, free
electrons are produced that attach to an O$_2$ molecule within $10^{-9}$ s. The O$_2^-$
molecule attracts a small number of water molecules, $W_n$, and owing to the high
concentration of O$_3$, ligand switching with O$_2$ is highly probable (Fahey et al.
1982). This results in a negative O$_3$/water cluster,

$$O_2^- \cdot W_n + O_3 \rightarrow O_3^- \cdot W_{n-1} + O_2 + W_1,$$

with a reaction constant of $7 \times 10^{-10}$ cm$^3$ s$^{-1}$. The above cluster initiates the
oxidation of SO$_2$ and a corresponding charge transfer is possible (Fehsenfeld &
Ferguson 1974),

$$SO_2 + O_3^- \cdot W_n \rightarrow SO_3^- \cdot W_n + O_2,$$

$$SO_2 + O_3^- \rightarrow SO_3^- + O_2,$$

where the reaction constant for reaction (6.3) is $1.7 \times 10^{-9}$ cm$^3$ s$^{-1}$. If the cluster
contains a sufficient number of water molecules, i.e. between 4 and 11, then SO$_3^-$
will react with the attached water molecules and form sulphuric acid (Larson
et al. 2000),

$$SO_3^- \cdot W_n \rightarrow H_2SO_4^- \cdot W_m.$$

The electron has now been involved in the stabilization and formation of a cluster
with a single sulphuric acid molecule, however, a stable cluster has to contain
several sulphuric acid molecules. The above reactions are ion reactions and the
reaction constants are close to the time-scales of gas kinetic collision, thus the time-
scale for generating a sulphuric acid molecule is ca 0.1 s for 200 p.p.t. SO$_2$. This
process continues to form H$_2$SO$_4$ molecules with the electron acting as a catalyst
and stabilizing the cluster while it is smaller than the critical size.

As indicated by the experimental results when using an electric field, the
residence time of an electron in the cluster is very short, i.e. 2 s or less. The
electron can become detached owing to excitation by a thermal photon or
the release of chemical energy within the cluster. The detached electron might
stabilize a new cluster, but there is a high probability that the electron is lost
through (i) attachment to larger stable clusters, and/or (ii) recombination with a
positive ion. In both the cases, the electron cannot form additional sulphuric acid
molecules. The number of stable clusters nucleated is then determined by the
typical residence time of an electron in a subcritical cluster and its

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attachment/recombination probability once detached. The studies involving negatively charged water clusters (Beyer et al. 2001) suggest that the electron detachment process can take between 100 and 0.02 s. The characteristic time identified above for producing a stable cluster (2 s or less) is well within this limit, a feature not reproduced by the existing ion-induced nucleation models (Yu & Turco 2001; Laakso et al. 2004; Lovejoy et al. 2004).

Finally, it should be stressed that the presence of trace amounts of other gases in the chamber cannot be excluded. It is possible that some trace gas may not have been absorbed by the filters, and might have contributed to the nucleation process. One candidate could be NH3 (see Kulmala et al. 2000). However, the presence of other condensable gases does not affect the main conclusion of this work, namely that the nucleation process under atmospheric conditions is proportional to the ion density.

The experimental data for both the burst and the steady-state experiments (figures 2a–4a) indicate that \( N(d>3\text{ nm}) \) is proportional to the small ion density, \( n_{e} \), such that \( N(d>3\text{ nm}) \propto I \propto n_{e} \). The numerical simulations indicate that \( N(d>3\text{ nm}) \propto S \), which leads to the semi-empirical relation between the production rate of stable clusters, \( S \), and the ion density, \( n_{e} \), viz. \( S = \alpha n_{e} \). Under the conditions of low background aerosol, the ion density is proportional to the square root of the ion production rate, \( q \). Note that this empirical relationship holds for both the burst and the steady-state experimental procedures. This allows for two independent estimates of the constant: for the burst experiment, \( a = 2.4 \times 10^{-4} \pm 0.4 \times 10^{-4} \text{ s}^{-1} \); and for the steady-state experiment, \( a = 2.3 \times 10^{-4} \pm 0.3 \times 10^{-4} \text{ s}^{-1} \). It is remarkable that the two different experimental procedures give the same nucleation constant. The observation that the particle production rates scale with the negative ion density suggests that it is the individual negative ions that are important, and not a collective effect between several ions, e.g. coagulation or recombination.

The experiment indicates that ions play a role in nucleating new particles in the atmosphere and that the rate of production is sensitive to the ion density. If this sensitivity is still relevant at the size of cloud condensation nuclei, one might expect to find a relationship between ionization and cloud properties (Svensmark & Friis-Christensen 1997; Svensmark 1998; Shaviv 2002). Marsh & Svensmark (2000) found that the correlation between cosmic ray ionization and clouds is mainly in low-level clouds and not as might have been expected, in high clouds where ionization variations are large.

This feature seems to be consistent with the present work. In the lower atmosphere, the limiting factor is the density of ions and, since the ion density (under conditions of low background aerosol) is proportional to \( \sqrt{q} \), the sensitivity of ion density to variations in the production rate increases for decreasing values of \( q \), i.e. \( dn_{e}/dq \propto q^{-0.5} \). In contrast, at higher altitudes in the atmosphere, the ion production rate can be 10 times larger than at the surface. In these regions, the role of ions saturates and the nucleation process is no longer sensitive to changes in ionization (Yu & Turco 2001). A response limited to regions where low-level clouds form is perhaps not surprising, especially when considering that high clouds usually consist of ice-particles, which involve nucleation processes not covered by the present work.

In summary, the present work indicates that (i) stable clusters are formed from SO2, O3 and H2O in the presence of ions, (ii) the experiments and
simulations suggest that an initial distribution of sub-3 nm stable clusters is formed containing H$_2$SO$_4$. (iii) the nucleation rate is proportional to the ion density, (iv) the negative ions are important, (v) the characteristic time for producing a stable cluster is very short 2 s or less, and (vi) the charge (electron) only stays on the small cluster for a short time 2 s or less.

References


