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On the potential of Cluster Ion Counter (CIC) to observe local new particle formation, condensation sink and growth rate of newly formed particles

Markku Kulmala[1,2,3], Santeri Tuovinen[1], Sander Mirme[4,5], Paap Koemets[4,5], Lauri Ahonen[1], Yongchun Liu[2], Heikki Junninen[4], Tuukka Petäjä[1,2,3] and Veli-Matti Kerminen[1]

[1] Institute for Atmospheric and Earth System Research (INAR)/Physics, University of Helsinki, Helsinki, 00014, Finland
[2] Aerosol and Haze Laboratory, Beijing Advanced Innovation Center for Soft Matter Science and Engineering, Beijing University of Chemical Technology, Beijing, 100089, China
[3] Joint International Research Laboratory of Atmospheric and Earth System Sciences, School of Atmospheric Sciences, Nanjing University, Nanjing, 210023, China
[4]Institute for Physics, University of Tartu, Tartu, 50090, Estonia
[5]Airel Ltd., Observatooriumi 5, 61602 Tõravere, Estonia

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Correspondence to: Markku Kulmala (markku.kulmala@helsinki.fi)

Abstract

Cluster Ion Counter (CIC) is a simple 3-channel instrument designed to observe ions in the diameter range from 1.0 to 5 nm. With the three channels, we can observe concentrations of both ion clusters (sub-2 nm ions) and intermediate ions. Furthermore, as derived here, we can estimate condensation sink, intensity of local new particle formation, growth rate of newly formed particles from 2 nm to 3 nm, and formation rate of 2 nm ions. We compared CIC measurements with those of a multichannel ion spectrometer, the Neutral cluster and Air Ion Spectrometer (NAIS), and found that the concentrations agreed well between the two instruments, with the correlation coefficients of 0.89 and 0.86 for sub-2 nm and 2.0–2.3 nm ions, respectively. According to the observations made in Hyytiälä, Finland and Beijing, China, the ion source rate was estimated to be about 2–4 ion pairs cm^{-3} s^{-1}.

1. Introduction

New particle formation (NPF) is the dominant source of the number concentration of aerosol particles in the global atmosphere (Gordon et al., 2017), thereby having potentially large influences on global climate (e.g. Boucher et al., 2013) and regional air quality (e.g. Guo et al., 2014; Kulmala et al., 2022). During the past 2-3 decades, atmospheric NPF has been characterized in terms of the particle formation and growth rates at a vast variety of sites in different atmospheric environments (Wang et al., 2017; Kerminen et al., 2018; Nieminen et al., 2018; Chu et al., 2019; Bousiotis et al., 2021). Such characteristics describe mainly regional NPF, i.e. NPF averaged over relatively large spatial scales of at least tens of km. Much less information is available about local NPF, or about the small-scale variability of regional NPF. Such information would be important in identifying hot spot areas for atmospheric NPF, or estimating the relative importance of various local sources to regional NPF.

https://doi.org/10.5194/ar-2024-14
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Atmospheric cluster ion (diameters below 2 nm) measurements can provide insight into ion source processes, such as the ion production rate associated with different atmospheric ionization pathways, as well as ion loss processes, such as ion-ion recombination or scavenging of ions by a pre-existing atmospheric aerosol population (e.g. Hirsikko et al., 2011; Kontkanen et al., 2013). Observations of intermediate ions (diameters between 2 and 7 nm) can be used to get information about atmospheric NPF (e.g. Tammet et al., 2014), whereas small intermediate ions (approx. 2–2.3 nm) can be used to detect "local" NPF, i.e. NPF taking place within a close proximity of a measurement site (Tuovinen et al., 2024).

Intermediate ions are sensitive to both occurrence and intensity of atmospheric NPF (e.g. Horrak et al., 1998; Tammet et al., 2014, Leino et al., 2016). Recently, Kulmala et al. (2024) and Tuovinen et al. (2024) found that the smallest sizes of intermediate ions describe relatively well the local production of new aerosol particles. These results were obtained using a Neutral Cluster and Air Ion Spectrometer (NAIS; Mirme and Mirme, 2013). The NAIS is, however, a sophisticated instrument that provides information not necessarily needed when investigating local NPF.

In this study, we will analyse data obtained using a Cluster Ion Counter (CIC; Mirme et al., 2024), a recently developed and simple 3-channel instrument, and will investigate how this instrument can be utilized to determine several variables important to NPF and small ion dynamics. Our main objectives are to derive simple equations for characterizing ion dynamics related to local NPF, and to find out whether the CIC is sensitive and reliable enough for such purposes. In order to reach these objectives, we will first derive equations that can be used to estimate condensation sink (CS), intensity of local new particle formation (actually local intermediate ion formation, LIIF), growth rate of newly formed particles and formation rate of 2 nm ions based on CIC measurements. Next, we will compare ion concentrations between the CIC and NAIS, as measured at the SMEAR II station in Hyytiälä, Finland. Finally, we will demonstrate how to apply CIC measurements in practice for obtaining information about local NPF and related quantities, including the condensation sink.

2. Material and Methods

2.1 Cluster Ion Counter (CIC)

The Cluster Ion Counter (CIC) is designed to be a simple and robust instrument for measuring total concentrations of small ions, and for obtaining some additional information about ion size distributions. The CIC has a low size resolution, with only three separate electrometers (Mirme et al., 2024). The mobility ranges of the three collecting electrodes of the original CIC were chosen to allow the estimation of average cluster ion mobility. However, the analyzer of the device can easily be modified to focus on other aspects of the mobility distribution.

A modified analyzer for the CIC was developed to estimate the concentration of intermediate ions roughly between 2 and 2.3 nm. Due to the relatively simple construction of the CIC, and specifically the absence of a separate sheath air flow layer in the mobility analyzer, the detection efficiency curves of the individual electrodes of the CIC are relatively wide and extend far towards larger particles (Figure 1). A higher size resolution can be achieved by looking at the difference of a signal between two separate channels. In the modified CIC, the signal from the first electrometer can be used to estimate the cluster ion concentrations. By

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

subtracting the signal of the third channel from the signal of the second channel, the concentration of intermediate ions roughly between 2 and 2.3 nm can be estimated. The third channel can be utilized for ions from 2.3 to 5 nm.

2.2 Conceptual model

The time evolution of sub-2 nm ion concentration, I, can be written as

$$\frac{dI}{dt} = Q - \alpha I^2 - \mathrm{CoagS_I} \times I, \qquad (1)$$

where Q is the ion source rate, α ($\approx 1.6 \times 10^{-6}$ cm^{-3} s^{-1}; Franchin et al., 2015) is the ion-ion recombination rate, and $\mathrm{CoagS_I}$ is the coagulation sink of the sub-2 nm ions onto pre-existing aerosol particles. In a steady state, we may approximate the left-hand side of eq.1 equal to zero, from which we obtain:

$$\mathrm{CoagS_I} = Q/I - \alpha I. \qquad (2)$$

The coagulation sink of particles of diameter d_p can be connected with the condensation sink (CS) of sulphuric acid monomers via (see Lehtinen et al., 2007)

$$\mathrm{CS} \approx \mathrm{CoagS}(d_p)\ (d_p/0.7\ \mathrm{nm})^m\ , \qquad (3)$$

where the exponent m depends on the shape of the pre-existing particle number size distribution, and the diameter of a sulphuric acid monomer is estimated to be 0.7 nm. By combining eqs. 2 and 3 we then obtain:

$$\mathrm{CS} \approx \mathrm{CoagS}(d_p = d_{p,I}) / \mathrm{CoagS_I}\ \ (d_p/0.7\ \mathrm{nm})^m\ \ (Q/I - \alpha\ I), \qquad (4)$$

where $d_{p,I}$ refers to the median diameter of the sub-2 nm ions. In order to simplify eq. 4, we will make three further approximations: 1) $d_{p,I}$ is equal to 1.2 nm for negative cluster ions observed with CIC, and 1.0 nm for negative cluster ions measured with NAIS, 2) the exponent m is equal to 1.6 (see Lehtinen et al., 2007), and 3) the ratio $\mathrm{CoagS}(d_p = d_{p,I})$ / $\mathrm{CoagS_I}$ is equal to 0.5 (Leppä et al., 2011; Mahfourz and Donahue, 2021). By combining these approximations, we finally obtain:

$$\mathrm{CS} \approx 1.2\ (Q/I - \alpha\ I). \qquad (5a)$$

$$\mathrm{CS} \approx 0.9\ (Q/I - \alpha\ I). \qquad (5b)$$

If I is measured with the CIC (NAIS), we can utilize eq. 5a (5b).

Similar to eq. 1, the time evolution of the concentration of the smallest (2–2.3 nm) intermediate ions, N, can be written as

$$\frac{dN}{dt} = J_2 - \mathrm{CoagS_N} \times N - J_{\mathrm{out}}, \qquad (6)$$

where J_2 is the formation rate of 2 nm ions, $\mathrm{CoagS_N}$ is the coagulation sink of the 2.0–2.3 nm ions onto the pre-existing aerosol population, and J_{out} is the rate at which these ions grow out of the 2.0–2.3 nm size range. $\mathrm{CoagS_N}$ and J_{out} can be approximated as:

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

$$\mathrm{CoagS_N} \approx \mathrm{CoagS_I} \times (1.2\ \mathrm{nm} / 2.1\ \mathrm{nm})^{1.6} \approx 0.4\ \mathrm{CoagS_I} \approx 0.4\ (Q/I - \alpha I)\ , \qquad (7)$$

$$J_{\mathrm{out}} \approx \mathrm{GR_{2.3\ nm}} \times N/\Delta \mathrm{d}, \qquad (8)$$

where $\mathrm{GR_{2.3\ nm}}$ is the growth rate of 2.3 nm ions and Δd (=0.3 nm) is the width of the intermediate ion channel of the CIC. Assuming a steady state ($\mathrm{d}N/\mathrm{d}t = 0$) and using Eqs. 2, 7 and 8, we then obtain:

$$J_2 = 0.4\ (Q/I - \alpha I) \times N + \mathrm{GR_{2.3\ nm}} \times N/\Delta d + \alpha IN. \qquad (9)$$

The last term in Eq. 9 accounts for the loss rate of 2.0-2.3 nm ions due to their recombination with sub-2 nm ions.

Particle (or ion) growth rates can be determined from the following equation:

$$\mathrm{GR} = \frac{\Delta d_i}{\Delta t}\ , \qquad (10)$$

where Δdi is the change of the diameter of ions over the time interval Δt as the ions grow in size. In section 3.2 we will demonstrate how the CIC measurement can be used for determining growth rates.

2.3. Observations

The CIC and NAIS were compared with each other at the SMEAR II station in Hyytiälä (Hari and Kulmala, 2005) during 16 Januray–01 April, 2024; however, NAIS data were missing from the period 16-17 March. The NAIS (Neutral Cluster and Air Ion Spectrometer) is a multichannel instrument to measure atmospheric ions from 0.8 to 42 nm and total particle concentrations from 2.5 to 42 nm (Mirme and Mirme, 2013). Furthermore, the conceptual model was used to analyse the data from both SMEAR II and AHL/BUCT station in Beijing, China (Liu et al., 2020). To produce Figure 6, 10%, 25%, 50%, 75%, and 90% small ion concentrations and CS values were used. The ion concentration values were also used in Figures 8 and 9. These data were taken from a different, longer time span than the data used for the CIC and NAIS comparison. For Hyytiälä, the data cover most of the time between the beginning of 2016 and end of 2020. For Beijing, ion concentrations were determined over the period 13 January 2018 to 01 April 2020, whereas the CS data cover the period 20 February.2018 to 31 March 2019. The particle number size distributions to derive the CS data were measured by a twin DMPS (Differential Mobility Particle Sizer; Aalto et al., 2001) in Hyytiälä and in Beijing by a particle size distribution (PSD) system (Liu et al., 2016). See Zhou et al. (2020) for more details on the measurements in Beijing.

3. Results and Discussion

3.1 Instrument comparison

In order to find out how reliably the CIC is able to observe ion concentrations, we compared it with the NAIS at the SMEAR II station in Hyytiälä, Finland. Tables 1 and 2 summarize the statistics of the ion concentrations measured by these two instruments for different size fractions. We can see that the total concentration of sub-2 nm negative ions measured by the

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

NAIS is significantly higher than those measured by the CIC (channel 1), the median concentrations being equal to 530 and 210 cm^{-3}, respectively. However, excluding the smallest ions measured by the NAIS, i.e. considering only the 1–2 nm size range, the median concentration drops down to 180 cm^{-3}. This is slightly below the median sub-2 nm concentration measured by the CIC, but only about one third of the median total sub-2 nm ion concentration measured by the NAIS.

A detailed comparison between the two instruments is in Figure 2 for small (<2 nm) ions, and in Figure 3 for the smallest size class of intermediate ions (2.0–2.3 nm). We can see that while the CIC shows somewhat larger small ion (1–2 nm) and lower 2.0–2.3 nm ion concentrations compared with the NAIS, the overall agreement between these two instruments is very good with the correlation coefficients of 0.85 and 0.86 for small ions and 2.0–2.3 nm ions, respectively.

Figure 4 presents the time series of ion concentrations measured by the CIC and NAIS over the whole two and half-month period, while Figure 5 presents the diurnal pattern of ions concentrations on a selected day (10th of March, 2024). Both size classes (sub-2 nm and 2.0–2.3 nm) agree pretty well between the two instruments, the correlation coefficient being around 0.9 on the selected day for both sub-2 nm ions and 2–2.3 nm ions. The peaks in 2.0-2.3 nm ion concentration are captured consistently by both instruments, and the concentration values of such peaks agree very well between the two instruments. Also the small ion concentrations agree well in terms of their peak values.

3.2 Application of CIC measurement in investigating condensation sink and local NPF

Figure 6 illustrates how the estimated condensation sink (CS) based on Eq. 5 behaves as a function of small ion concentrations, I, for different ion production rates. In the same plot, we have included the observed variability of CS and I in both Hyytiälä and Beijing. We can see that measured and theoretically calculated values of CS agree with each other the best when median ion production rates are between about 2 and 4 ion pairs cm^{-3} s^{-1} in both Hyytiälä and Beijing.

The CIC has a higher detection efficiency for small ions than the NAIS due to a shorter inlet tract, and consequently, lower inlet losses. However, in case of both instruments, the detection efficiency for sub-2 nm ions is very strongly dependent on a particle size. The NAIS measures the size distribution of ions, and the data inversion algorithm uses that information to correct for the size-dependent detection efficiency. The CIC has limited information about the size distribution of detected ions, making it more difficult to correct for the detection efficiency. Using inverted ion size distribution data from the NAIS and uncorrected ion concentration data from the CIC (Tables 1 and 2), we estimated how the concentrations measured using the CIC and NAIS will influence the estimated values of CS. By using eq. 5 and by assuming the median sub-2 nm ion concentrations measured by these two instruments (Tables 1 and 2), we may calculate that the values of CS measured using the NAIS are 0.237, 256 and 0.266 times those measured using the CIC for Q equal to 2,3 and 4, respectively. Therefore, if we use the CIC for estimating CS via eq. 5a, the real CS (using NAIS and equation 5b) is about 0.25 times the one observed by CIC.

In order to illustrate how the CIC can be used to determine the growth rate, we selected one measurement day (Figure 7). We used the appearance time method (e.g. Lehtipalo et al., 2014) from channel 3 and the difference between channels 2 and 3. The difference in

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

channels gives the concentration in size range of 2.0–2.3 nm. The peak in the collection efficiency curve of channel 3 is approximately 2.9 nm (see Figure 1). So comparing the appearance time in those channels we can determine the growth rate from 2.1 to 2.9 nm to be about 1.0 nm/h. This value can be considered a very realistic one, as the earlier long-term measurements at the same site indicate typical growth rates between about 1 and 2 nm/h for sub-3 nm ions (Hirsikko et al., 2005; Manninen et al., 2010). We should note, however, that it is not possible to determine growth rates for all measurement days using the procedure illustrated in Figure 7. This is because even if an increase in ion concentrations was observed, the signal might be too noisy, making the determination of appearance times too unreliable. In addition, not all days exhibited a clear delay between the two appearance times, making the determination of growth rate impossible.

Using eq. 9, we can estimate the formation rate of 2 nm ions, J_2. Figures 8 and 9 show these formation rates for Hyytiälä and Beijing, respectively. This formation rate can be given as a function of the measured number concentrations of 2.0–2.3 nm intermediate ions, in addition to which J_2 depends on the growth rate, ion source rate, and ion loss rate. J_2 also depends on the concentration of sub-2 nm ions, which is determined by the ion loss rate and ion source rate (Eq. 1). The most probable values are 1–2 nm/h for the growth rate in Hyytiälä (Figure 7, Hirsikko et al., 2005; Manninen et al., 2010), 1–3 nm/h for the growth rate in Beijing (Deng et al., 2020), and 2–3 cm^{-3} s^{-1} for the ion source rate (Figure 6). However, also higher values are given for comparison. Manninen et al. (2010) calculated a median value of 0.06 cm^{-3} s^{-1} for J_2 based on long-term measurements in Hyytiälä, which is at the higher end of values estimated in Figure 8. Compared with Hyytiälä, we estimate a factor of 2–4 larger values of J_2 for Beijing. In both places, the total formation rate of 2 nm particles is considerably larger than the formation rate of 2 nm ions, being of the order of one magnitude in Hyytiälä (Manninen et al., 2010, Kulmala et al., 2013) and even larger in Beijing (Deng et al., 2020).

Figure 10 shows the estimated time evolution of the condensation sink and 2-nm ion formation rate during one day. The value of CS varies only little, less than a factor of 1.5, whereas the ion formation rate varies by more than two orders of magnitude during the day. We can clearly see that when CS is at its lowest at around midday, the ion formation rate is at its highest.

4. Conclusions and summary

The recent progress of finding local NPF (e.g. Kulmala et al., 2024; Tuovinen et al., 2024) has opened a question: are we able to utilise a simple ion counter to find out LIIF in a proper way. According to our results presented above, the answer is: yes.

We have developed a somewhat modified version of the CIC to measure sub-2 nm ion and 2.0–2.3 nm ion concentrations as accurately as possible (Mirme et al., 2024). From the latter quantity we can estimate LIIF (Kulmala et al., 2024; Tuovinen et al., 2024), and from the former quantity we get information on the dynamics of small ions, including an estimate of ion sinks and via equations (2) and (5) also condensation sink. Furthermore, the CIC makes it possible to estimate the growth rate from about 2 nm to 3 nm and, with this information, the formation rate of 2-nm ions. While we have focused on negative ions in this paper, the same is also valid for positive ions. LIIF is more sensitive to negative ions (Tuovinen et al., 2024), and thus negative ions were investigated.

The comparison of the estimated condensation sinks with the observed ones in Hyytiälä and Beijing shows that the CIC, together with the simple theoretical framework, is able to give relatively accurate estimates on the condensation sink, ion sinks and ion formation rates. We also compared the CIC with the NAIS in Hyytiälä, which demonstrates that the measured ion concentrations agree pretty well. Therefore, we can conclude that the CIC is an effective instrument to observe LIIF and CS. However, if we want to investigate aerosol formation and growth rates for the nucleation mode (3–25 nm), as is usually the case in investigating regional NPF, NAIS measurements are needed.

Author contribution

Markku Kulmala had the original idea after discussions with Heikki Junninen. SM and PK developed the CIC. LA performed CIC and NAIS comparison in Hyytiälä. ST and MK analyzed the data. VMK and MK derived the used equations. YL lead the observations in Beijing and TP in Hyytiälä. HJ, VMK, TP and ST contributed to developing the idea further. MK, VMK and ST wrote the first version of the paper. All coauthors contributed the final version of the paper.

Competing interests

Markku Kulmala is a member of the editorial board of Aerosol Research. The authors have no other competing interests to declare.

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Preprint. Discussion started: 27 May 2024

Tables

Table 1. Statistics of the CIC Channel 1 (small ion) and Channel 2–3 (roughly 2–2.3 nm ion) concentrations (cm^{-3}) during 16.01.2024–01.04.2024. Positive polarity is marked by + and negative by –. The negative concentrations for the Channel 2 subtracted by Channel 3 are indicative of a noisy signal of the instrument.

	Channel 1		Channel 2 - Channel 3	
	+	–	+	–
Mean	280	220	2.8	5.2
10%	130	90	–11	-13
25%	190	140	–4.4	-5.6
50%	270	210	1.3	0.9
75%	360	290	7.9	9.6
90%	430	380	17	24

Table 2. Statistics of NAIS concentrations (cm^{-3}) during 16.01.2024 – 01.04.2024, excluding 16–17.03.2024. Small ions in the diameter ranges 0.8–2 nm and 1–2 nm are included. Intermediate ion concentrations are included for diameter range 2–2.3 nm, as well as for the diameter range that the CIC covers (virtual CIC Ch 2–3). Ch 2–3 concentrations have been calculated by multiplying the NAIS ion concentrations by detection efficiencies presented in Figure 1, after which they have been summed and divided by the average detection efficiency. Positive polarity is marked by + and negative by –.

	0.8–2 nm		1–2 nm		2–2.3 nm		Virtual CIC channel 2–3	
	+	–	+	–	+	–	+	–
Mean	490	540	400	210	2.0	2.3	17	13
10%	360	400	270	95	0.2	0.04	8.7	2.8
25%	410	460	330	120	0.7	0.3	11	4.5
50%	490	530	400	180	1.5	1.1	14	7.5
75%	570	620	470	270	2.7	2.6	19	14
90%	640	700	540	380	4.2	4.8	29	26

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

Figures

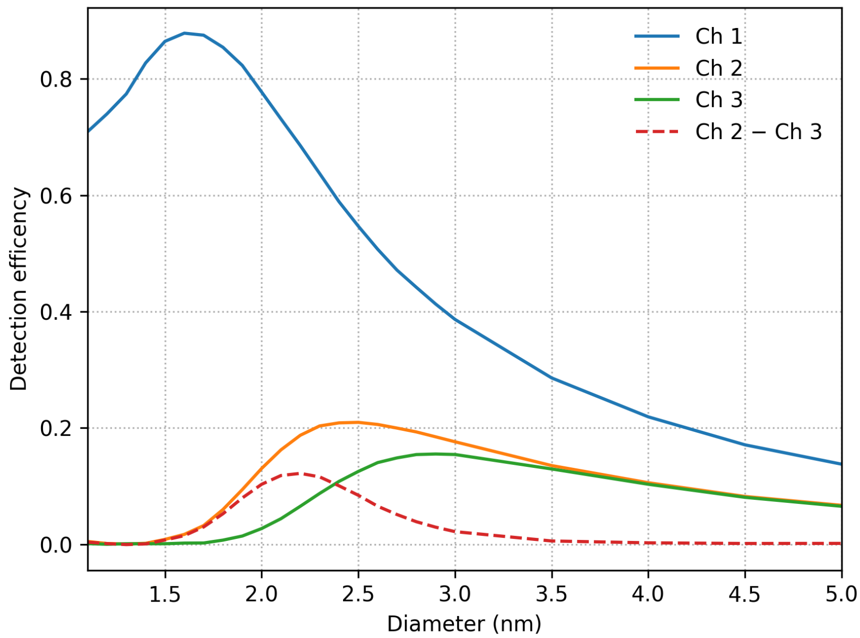

Figure 1. Experimental detection efficiency for ions in the range from 1.1 to 5.0 nm for each of the 3 collecting electrodes of the CIC. Due to the absence of a separate sheath air flow layer in the mobility analyzer, the detection efficiencies do not have a sharp upper size limit; instead, they asymptotically approach zero as particle size increases. Ion concentrations in a narrower size range can be estimated by subtracting the signal of channel 3 from channel 2. The detection efficiencies of the two channels converge from 2.5 nm to 3.5 nm and are practically equal for larger particles.

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

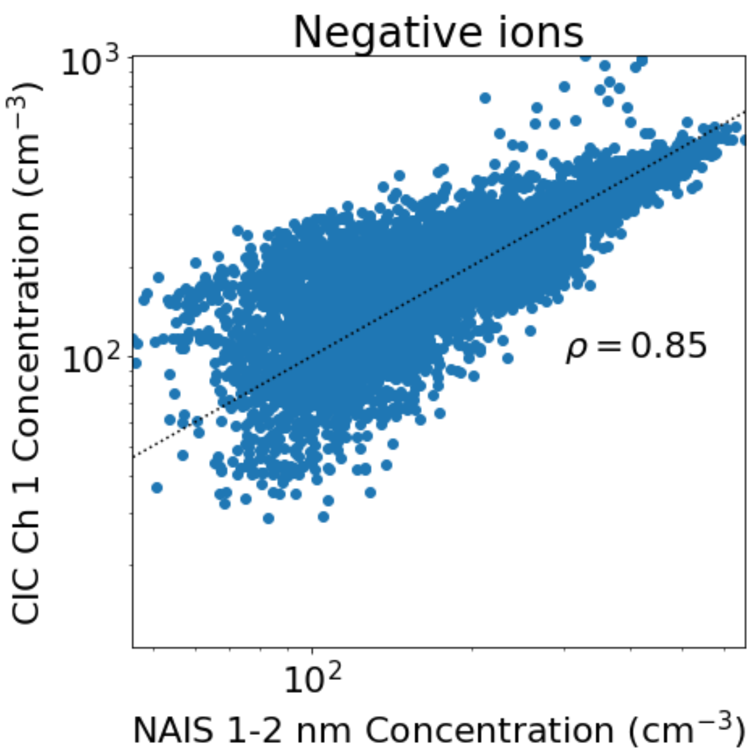

Figure 2. Scatter plot of the 15-min median negative small ion concentration measured with the CIC as a function of the concentration measured with the NAIS in Hyytiälä during 16.01–01.04. 2024. The values are missing from the period 16–17.03.2024. The NAIS concentrations are from the diameter range 1–2 nm, while the CIC concentrations are from Channel 1. The black dotted line marks the 1:1 line. Pearson correlation coefficient ρ of the two concentrations shown is included in the figure.

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

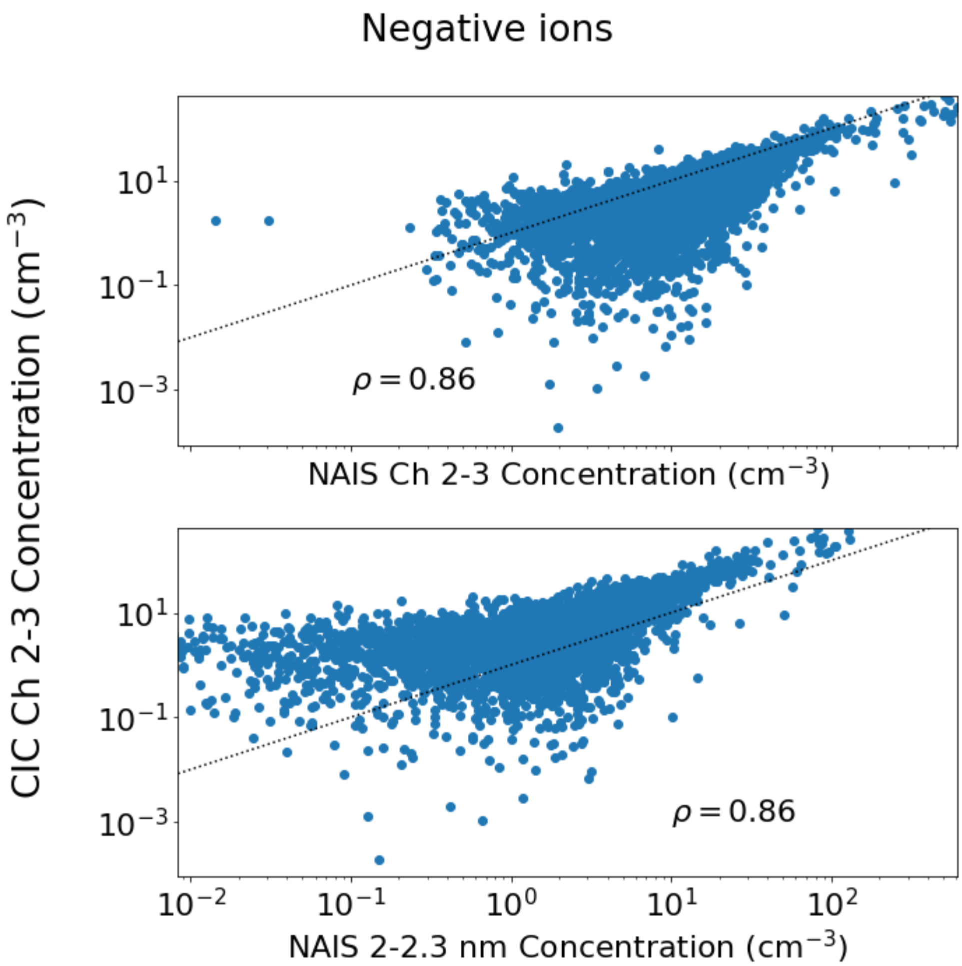

Figure 3. Scatter plot of approximately 2.0–2.3 nm negative ion 15-minute-median concentrations measured with the CIC as a function of concentrations measured with the NAIS in Hyytiälä during 16.01–01.04. 2024. The values are missing from the period 16–17.03.2024. The NAIS concentrations on the top figure were determined for the same size range as covered by the CIC Channels 2 and 3. The concentrations from the NAIS were multiplied by the detection efficiencies for the CIC Channel 2–3 presented in Figure 1, summed and divided by the average detection efficiency for the CIC channel 2–3. If the NAIS concentrations are assumed to be equal to the atmospheric concentrations, then in theory the CIC and NAIS concentrations in the top figure should be equal. The NAIS concentrations on the bottom figure are for the diameter range 2–2.3 nm. The black dotted line marks the 1:1 line. Pearson correlation coefficient ρ of the two concentrations shown is included in the figure. The NAIS concentrations in the top figure are on average higher, which is due to the wider size range of ions covered.

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

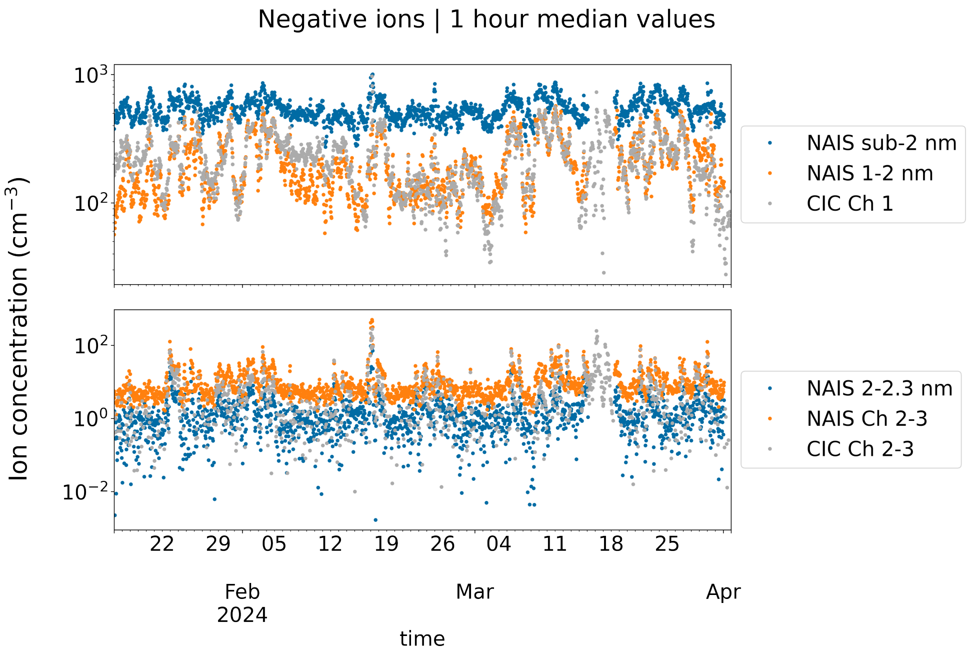

Figure 4. Time series of observed ion concentrations (16.01.2024–01.04.2024). The NAIS data are missing from the period 16–17.03.2024. The top figure has the concentrations of small ions from the CIC Channel 1 and from the NAIS for both all sub-2 nm ions and 1–2 nm ions. The bottom figure has concentrations of ions measured by the CIC channel 2–3 which approximately corresponds to the size range of 2–2.3 nm. In addition, there are concentrations of 2–2.3 nm ions measured by the NAIS (NAIS 2–2.3 nm) and concentrations from the NAIS that were derived by multiplying the NAIS concentrations by the CIC detection efficiencies presented in Figure 1 and then summed and divided by the average CIC concentrations (NAIS Ch 2-3). In theory, if the concentrations measured by NAIS are assumed to equal to the atmospheric ion concentrations, then the CIC Ch 2–3 and NAIS Ch 2–3 concentrations should be equal.

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

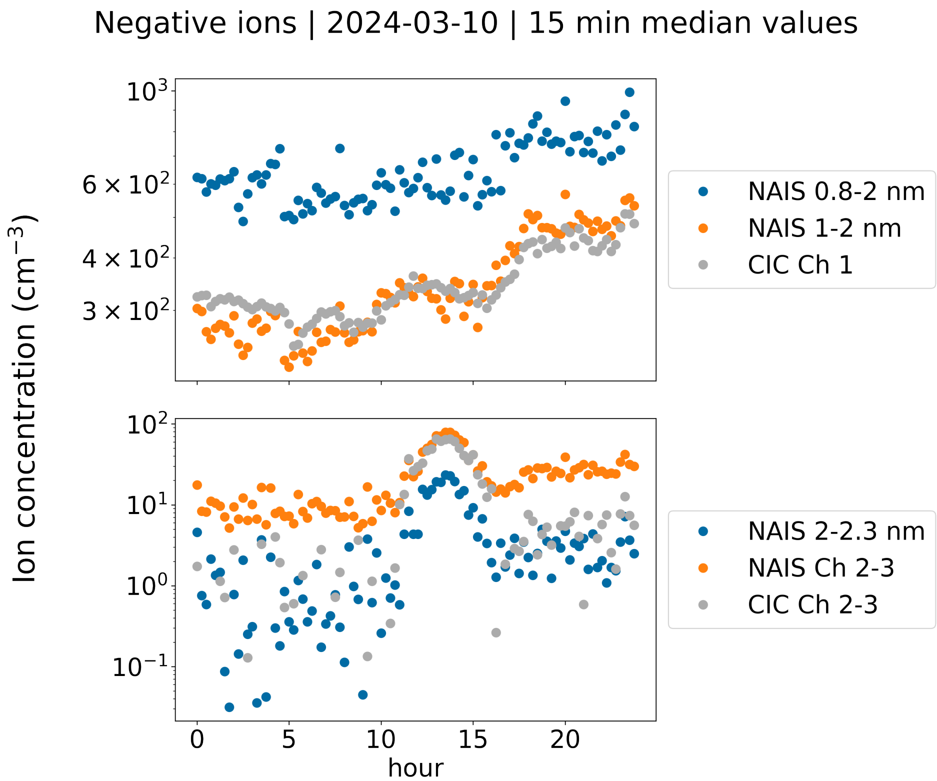

Figure 5. Observed negative ion concentrations on 10.03.2024. The top figure has the concentrations of small ions. For CIC, they are from the CIC Channel 1. From the NAIS, concentrations for all sub-2 nm ions and based on the size range 1–2 nm are included. The top figure illustrates how the CIC concentrations are correspond closely to the concentrations of 1–2 nm ions, while ions smaller than are not detected. The bottom figure has the concentrations of intermediate ions. For CIC, they are from Channel 2–3, corresponding to roughly 2–2.3 nm size range. For NAIS, the concentrations of ions between 2 and 2.3 nm are included, as well as the concentrations derived by multiplying the NAIS concentrations by the CIC detection efficiencies presented in Figure 1 and then summed and divided by the average CIC concentrations (NAIS Ch 2–3). In theory, if the concentrations measured by the NAIS are assumed to equal the atmospheric ion concentrations, then the CIC Ch 2–3 and NAIS Ch 2–3 concentrations should be equal. When the concentrations are higher around midday, this is indeed the case. The correlation coefficients on this day are 0.83, 0.95, 0.93 and 0.90 for NAIS 0.8-2 nm vs CIC Channel 1, NAIS 1–2 nm vs CIC Channel 1, NAIS 2-2.3 vs CIC Channel 2–3, and NAIS Channel 2–3 vs CIC Channel 2–3, respectively.

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

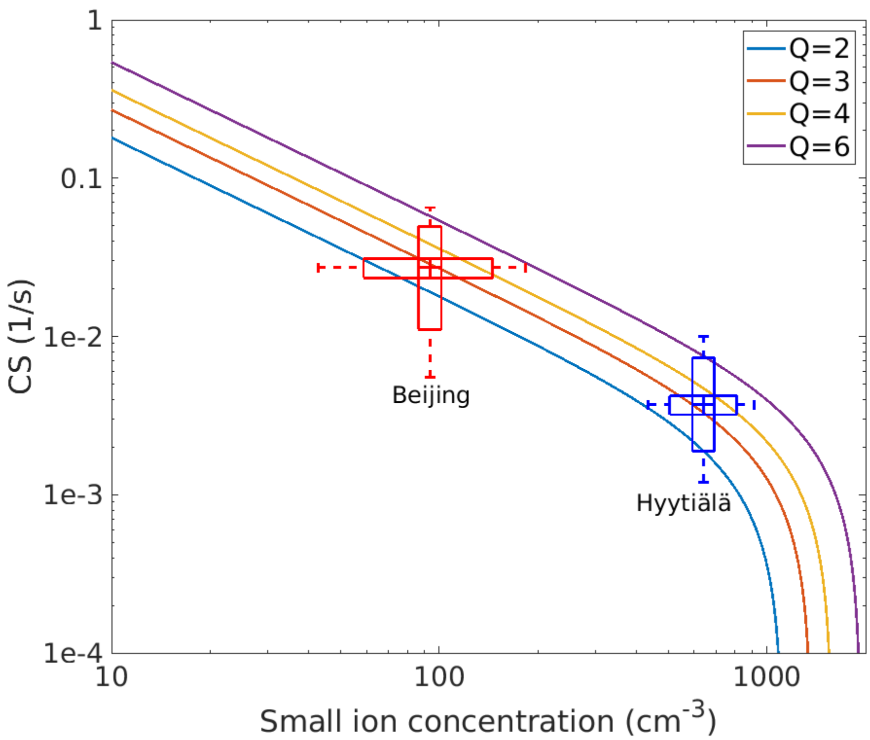

Figure 6. Condensation sink (CS) as function of the small ion concentration for different ion source rates (Q, ions cm^{-3} s^{-1}). The observed values of N and CS in Hyytiälä and Beijing (medians marked by the center line of the boxplot, 25% and 75% quartiles marked by the edges, and 10% and 90% percentiles marked by the whiskers of the boxplots) indicate ion source rates between about 2 and 4 cm^{-3} s^{-1} in both places. For Hyytiälä, the data covers most of time from the beginning of 2016 to the end of 2020. For Beijing, the ion concentrations are determined based on the values from 13.01.2018 to 01.04.2020, whereas the CS data cover the period 20.02.2018 to 31.03.2019.

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

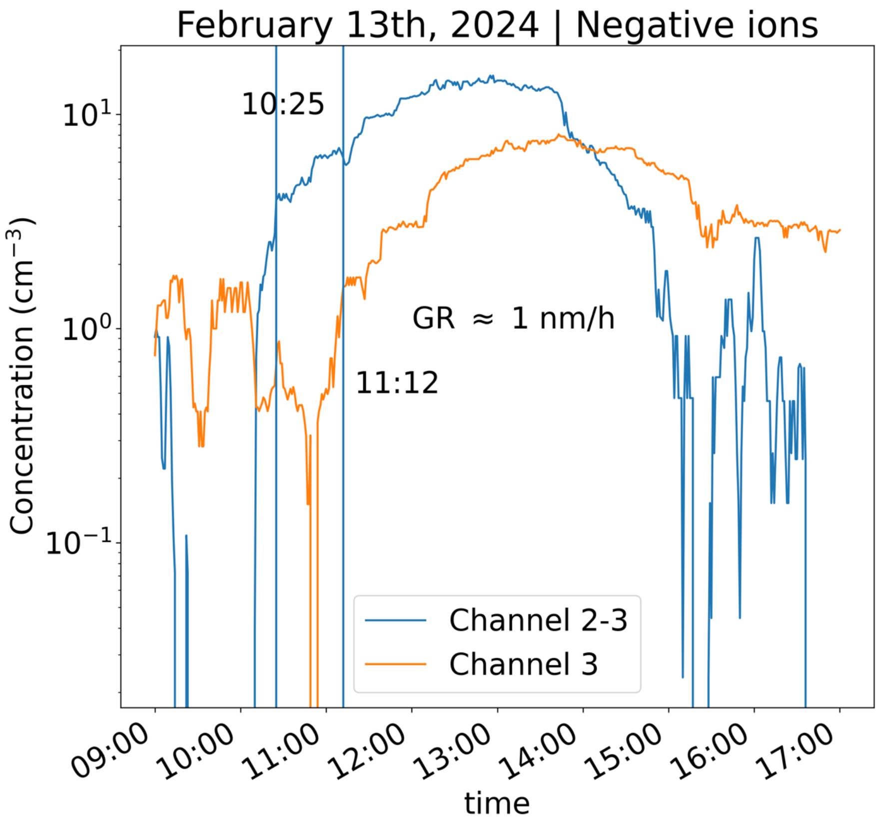

Figure 7: Determining an approximation for ion growth rate (GR). The ion concentrations were smoothed using a moving 1-hour median method to lessen the impact of noise. Channel 3 and Channel 2–Channel 3 concentrations have a similar shape between 10:00 and 16:00, and the shape of the Channel 3 roughly follows that of Channel 2–3 with a time delay. Considering the shape and features of the two curves, and the times at which the two concentrations reach a similar fraction of the maximum concentration (similar to appearance time method), two time instances were identified visually. The ion concentrations are around 0.2 of the corresponding maximum concentrations at these times. From these approximate appearance times, a time delay is gained and assuming the diameters of 2.1 nm and 2.9 nm for Channel 2–3 and 3, respectively, we obtain a GR of about 1.0 nm/h. We note that on this particular example day, the curves follow each other closely for a span of several hours, so that the value of GR is not very sensitive to the identified appearance times, i.e., the chosen fraction of the maximum concentration anywhere between 0.2 and 0.9 results in the same approximate GR ≈ 1 nm/h. However, if the two concentration curves are not as similar, and if there is variation in the features, more care in identifying the appearance times may be needed.

https://doi.org/10.5194/ar-2024-14
Preprint. Discussion started: 27 May 2024

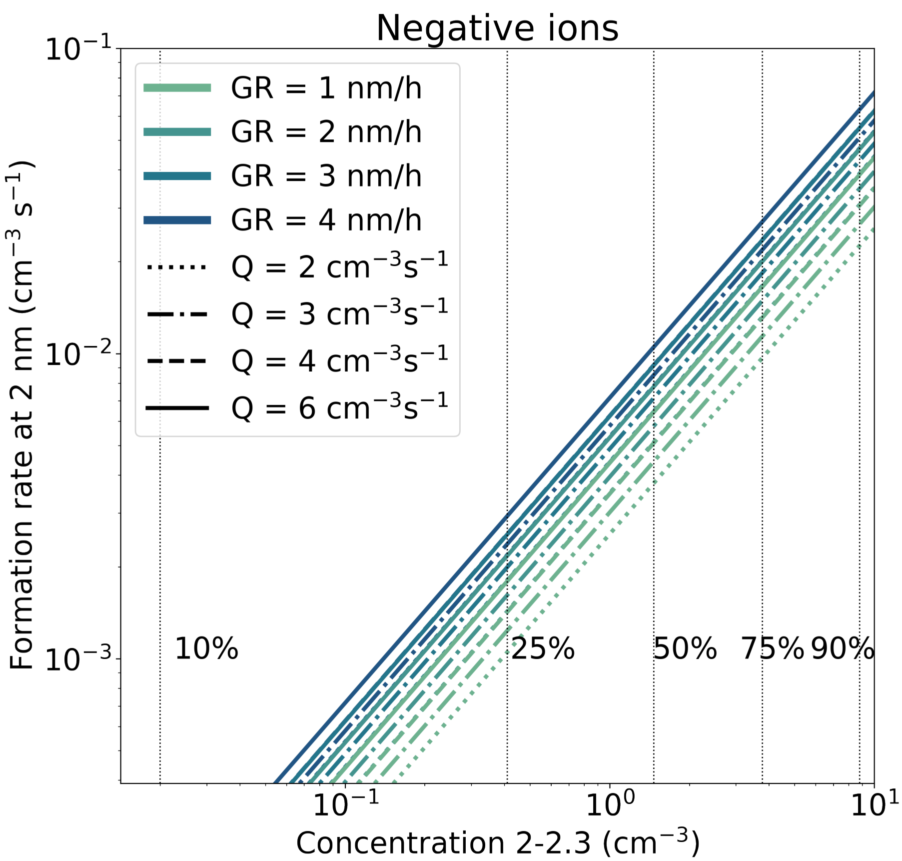

Figure 8. The estimated formation rate of 2-nm ions (negative ions). The formation rate using the GR of 1 nm/h can be estimated as a function of concentration of 2.0–2.3 nm size ions in Hyytiälä. The 10%, 25%, 50% (median), 75%, and 90% concentration values from Hyytiälä are indicated by the vertical dotted lines.

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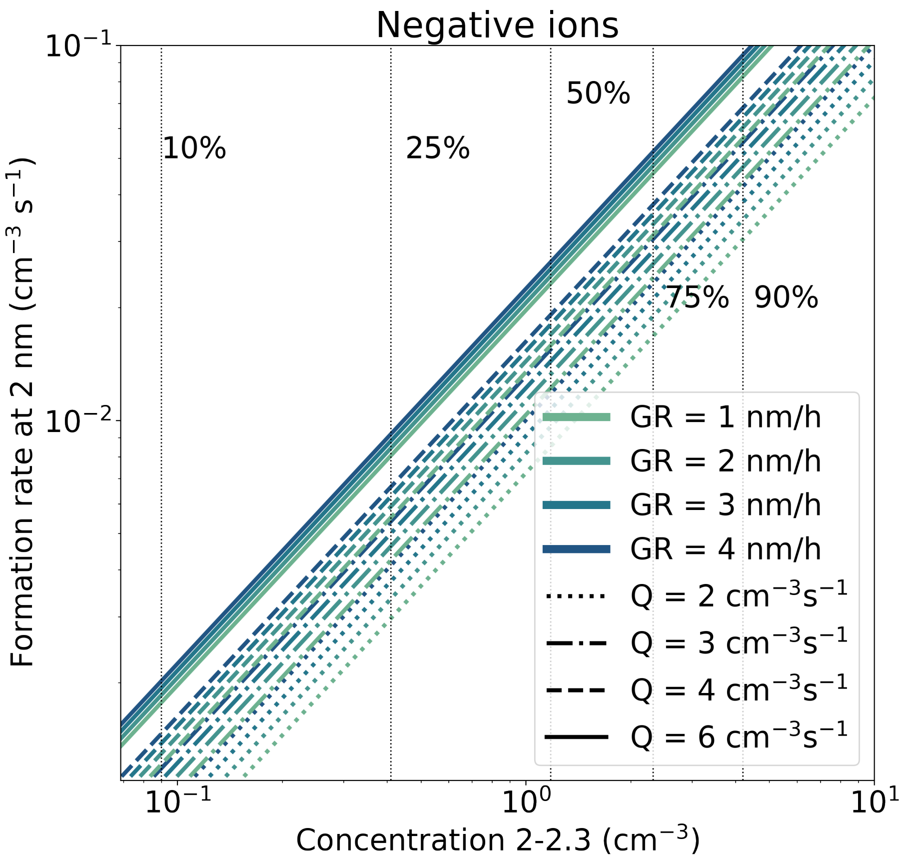

Figure 9. The estimated formation rate of 2 nm ions (negative ions). The formation rate using the GR of 1 nm/h can be estimated as a function of concentration of 2.0-2.3 nm size ions in Beijing. The 10%, 25%, 50% (median), 75%, and 90% concentration values from Beijing are indicated by the vertical dotted lines.

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Preprint. Discussion started: 27 May 2024

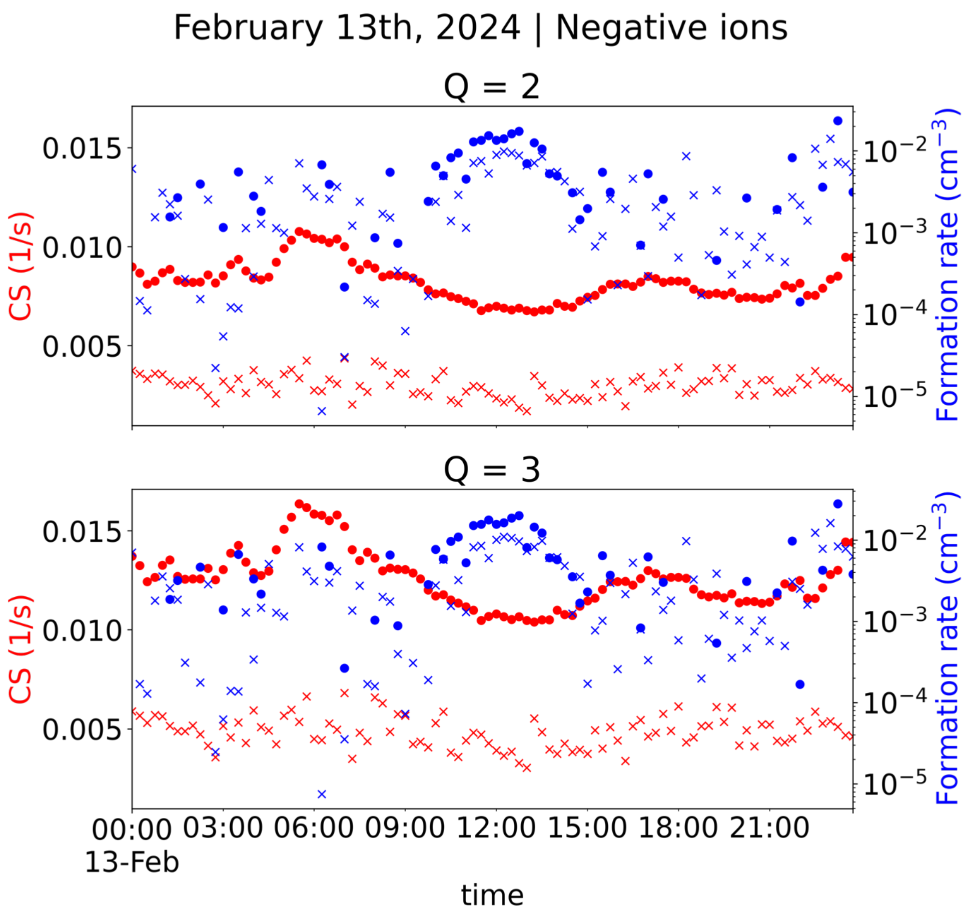

Figure 10: Condensation sink (right) and formation rate of 2 nm ions (left). The values marked by dots are based on CIC channel 1 and channel 2-3 ion negative ion concentrations while the values marked by x markers are based on NAIS sub-2 nm and 2-2.3 nm negative ion concentrations. The top panel has valued with assumed ion source rate of Q= 2 cm^{-3} s^{-1} while the bottom panel includes those for Q=3 cm^{-3} s^{-1} . A value of 1 nm/h for GR used, as determined in Fig. 7 for this day. Negative and positive ion concentrations were assumed to be the same.