



Blowing snow at coastal Antarctica: a source of ions and sodium chloride clusters

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Abstract. Strong winds accompanied with flying snow produce high concentrations of air ions and small ion clusters. The physical production mechanisms and the chemical nature of those clusters have remained an open question. We measured the ion cluster concentration and their chemical composition at Neumayer III station in Queen Maud land, Antarctica, during a 3-month measurement campaign from Nov 2018 – Feb 2019. We found that negative ion clusters are mostly composed of sodium chloride (NaCl). The chloride (Cl⁻-ion) was the most abundant core ion and charge carrier in the observed clusters. Other identified core ions included MnO⁻, I⁻, IO₃⁻, NaO⁻, NaO₂⁻, SO₃⁻, HSO₄⁻, NO₃⁻, O₂⁻, CaCl⁻ and HS⁻. The concentration of 0.8 – 2 nm ion clusters during blizzards were 30-fold compared to fair weather conditions, reaching 10⁴ cm⁻³ with wind speeds exceeding 18 m s⁻¹. Our observations are important for a comprehensive understanding of ionization and ion cluster production in Antarctica's atmosphere. Negative ion induced nucleation of sulfuric acid and ammonia is the main new particle formation mechanism in Antarctica and the nucleation rate is dependent on ion concentration. Snowstorms and ions produced within the blizzard could serve as an additional source of ions for subsequent new particle and eventually cloud condensation nuclei production.

1 Introduction

Atmospheric small ions (sub-2 nm) are primarily produced by galactic cosmic radiation with a rate of ca. 2 ion pairs cm⁻³ s⁻¹ as well as by terrestrial radiation and radon decay with a location dependent rate of ~0 – 10 ion pairs cm⁻³ s⁻¹ (Smith and Spangel, 1995). In Antarctica, due to thick glacial ice and snowpack, latter mechanisms are of very little importance. Primary ions (e.g. N₂⁺ and O₂⁺) rapidly react with atmospheric trace constituents and transfer their charge to the most acidic (negative) or basic (positive) molecules leading to the production of compounds such as HSO₄⁻ (Beck et al., 2021; Jokinen et al., 2018) and IO₃⁻ (Beck et al., 2021; Sipilä et al., 2016) which serve as core ions in ion-induced secondary new aerosol particle formation in



polar atmosphere. New particle formation accounts for half of cloud condensation nuclei (CCN) globally and up to 80% in Antarctica (Gordon et al., 2017). Molecular scale observations made at Aboa (Jokinen et al., 2018), a close-coastal Antarctic site, and at Marambio (Quéléver et al., 2022, Boyer et al., 2025), Antarctic Peninsula, indicate that summertime new particle formation is initiated via ion-induced nucleation of sulfuric acid (H_2SO_4), ammonia (NH_3) and water (H_2O) with subsequent growth by condensation of sulfuric acid and to lesser extent by ammonia, methane sulphonic acid ($\text{CH}_3\text{SO}_3\text{H}$, MSA) and iodic acid (HIO_3). In regions close or over the sea ice, iodic acid and/or other iodous compounds could have more pronounced role in nucleation and growth process similar to Arctic ice-covered regions (Beck et al., 2021; He et al., 2021; Sipilä et al., 2016). Regardless of which compounds drive nucleation, atmospheric ions strongly enhance the nucleation rate by roughly a factor of 10 in Antarctic atmosphere, as demonstrated experimentally for the H_2SO_4 - NH_3 - H_2O system (Kirkby et al., 2011) and for iodine oxoacid (HIO_x) / iodine oxide system (He et al., 2021).

Besides ionizing radiation, ions can be produced by rain (Kolarž et al., 2012; Manninen et al., 2010; Tammet et al., 2009) and, prominent for Antarctic atmosphere, strong winds associated with blowing snow (Simpson, 1921). The first hint toward wind-induced ion production dates back to the Scott's Terra Nova British Antarctic Expedition 1910 – 1913, where Simpson (1921) discovered that blowing snow conditions in the Antarctic atmosphere are enhancing its positive potential gradient. The maximum measured potential gradient was detected during wind speeds exceeding 40 miles per hour ($\sim 18 \text{ m s}^{-1}$). Similar observations made over the years, have shown that blowing snow particles indeed produce electric potential in the atmosphere. Later studies have found electric field strengths from a few kV m^{-1} (Savelyev et al., 2006) up to 30 kV m^{-1} (Schmidt et al., 1999) during blizzards which is approximately thousand-fold compared to the fair weather field strength. The polarity of the field can also change frequently.

Similar to charge dipole in thunderclouds, low level electrical potential gradient in a snowstorm requires vertical charge separation which, in turn, implies the presence of concentrated air ions, charged particles, ice crystals or snowflakes. The positive gradient (Simpson, 1921) could be explained by assuming that storm generates charged particles and that the lighter positively charged particles could distribute more easily vertically, while the heavier particles with the negative charge remain in the lower levels. The opposite would be true for the negative potential gradient. Observations by Nishimura and Nemoto (2005) suggest that the amount of smaller snow particles ($< 100 \mu\text{m}$) during blowing snow events increases with height, while in the lower levels they measured a mixture of snow particles in all sizes. Thus, size-dependent charge separation – in which smaller, lighter particles carrying one polarity of charge are lifted higher than larger particles carrying the opposite polarity – would readily explain the potential gradient in blowing snow.

In any case, the potential gradient requires the presence of charged crystals, flakes, particles or air ions in the blowing snow. Recent deployments of air ion spectrometers (e.g. AIS, Airel Ltd., Asmi et al., 2009; Mirme et al., 2007) in various locations have, indeed, revealed that blowing snow conditions are usually associated with elevated concentrations (thousands of ions



cm⁻³ in comparison to clear sky concentration of few hundred cm⁻³) of small (<2nm) and intermediate sized (2-7 nm) air ions. Virkkula et al. (2007) observed intensive ion production at the Finnish Antarctic research station Aboa, Queen Maud Land, during snowstorms and Chen et al. (2017) made the same observation at the Concordia station at Dome C, Antarctic plateau. Manninen et al. (2010) detected ion formation at snowy European sites – including Jungfrauoch (Switzerland) and Puy de Dome (France) mountains as well as at Pallas fell, Finnish Lapland – during strong winds. All of the above cited observations were made by an instrument (AIS) which is incapable of measuring charged particles larger than 40 nm. Therefore, those findings do not exclude the presence and the role of larger charged ice particles or snowflakes in contributing to the potential gradient and the exact contribution of these nanometer-range air ions to the generation of the gradient as well as their formation pathways and chemical compositions remain unresolved.

The detailed mechanisms producing charge and small ions during snowstorms remain unclear, however several pathways have been proposed. The hypothesis by Chen et al. (2017) states that intermediate ions form via ion-induced nucleation of vapours evaporated from snowflakes, but this does, however, not explain how the initial charges on which such vapours would nucleate are produced originally. Virkkula et al. (2007) observed flying snow sublimation during snow storms, indicating that the crystals shrink in size. During the sublimation, salts and other impurities of the snow can get airborne and carry one or more elementary charges. Potentially, if the impurities stay inside the crystal, the shrinking could also cause a Coulomb fission at Rayleigh limit due to the repulsive forces of the multiple charges, leading to a breakage of the crystal, analogous to the fission of liquid droplets in the electrospray process (Fraser and Beauchemin, 2009; Harris and Stace, 2018). The resulting daughter ions could continue the sublimation and undergo further fissions until solid charged particles, detectable by the ion spectrometer, remain. Another possible mechanism is the ejection of ions, charged particles or droplets by Rayleigh jets, in which the ice body stays otherwise intact while charged material is ejected into the surrounding atmosphere. These charged particles can subsequently undergo Coulomb fissions upon sublimation. A third possibility is corona discharge, in which the electric field at the sharp tip of a crack in the ice particle temporarily exceeds the discharge threshold, producing ions near the tip. Both these mechanisms – Rayleigh jets and corona discharge - have been discussed in detail in a review article by (Tkachenko and Jacobi, 2024).

Besides sublimation-driven effects, charge separation may also occur through mechanisms known from thunder clouds, where multiple pathways producing charged crystals, droplets, and graupel pellets have been proposed for liquid, ice and mixed-phase clouds. These mechanisms are comprehensively summarized by Saunders (2008). One such pathway involves the collision of graupel pellets and small ice crystals which transfers charge between those two (Reynolds et al., 1957) in a temperature dependent direction (Takahashi, 1978). A second pathway, suggested by Latham and Mason (1961), involves temperature gradients within ice particles (crystals / snowflakes / graupels) caused by riming during collisions with supercooled droplets or in blowing snow rather than sublimation of ice (Saunders, 2008 and references therein). The temperature gradient is assumed to distribute H⁺ and OH⁻ ions such that opposite charges accumulate at the outer or the inner region of the ice



particle. Subsequent mechanical collisions then break out the surface charge, while the interior charge remains inside the snowflake or ice crystal. Collisions between cooler and warmer particles can also lead to charge transfer between ice particles. A third suggested pathway involves a phase change: Melting graupel can eject charged droplets in clouds (Drake, 1968), while rapid freezing of a supercooled cloud droplet can localize charge and trigger dissociation, known as Workman-Reynolds effect (Gross, 1965; Haymet and Wilson, 2017). Freezing during collisions between liquid droplets and ice particles can likewise produce charged ice fragments (Hallett and Saunders, 1979). These melting / freezing mechanisms require a thaw-freeze cycle which is commonly observed on snow or firn surfaces, especially during summer. However, blizzards mostly occur during temperatures below zero degrees of Celsius, which do not favor ice crystal melting and ion production. Snowstorm induced ion production has been observed in very cold conditions on Antarctic plateau (Chen et al., 2017), indicating these phase-change mechanisms cannot be the sole explanation.

Regardless of how these ions form, they are too small, below 10 nm in diameter, to act as cloud condensation nuclei (CCN) or to cause climatic effects. However, a fraction of them could survive the storm and either transfer their electrical charge leading to formation of HSO_4^- or IO_3^- , known seed ions for ion induced nucleation as mentioned previously, or act themselves as seeds for condensation of condensable vapours leading to growth above 20 nm in diameter, the smallest size of particles that have been shown to be able to serve as CCN (e.g. Beck et al., 2021; Karlsson et al., 2021). Moreover, collisions between negative and positive intermediate ions could lead to the formation of stable neutral salt particles that can escape the storm and may as well then grow further when subjected to elevated concentrations of condensing vapours. However, the relevance of snowstorm produced ions to CCN budgets has never been quantified.

Blowing snow in the Antarctic atmosphere is not only producing small, charged particles, but has been shown to play a major role in sea salt aerosol (SSA) concentrations. Sodium chloride (NaCl) is known to be the major component of coastal Antarctic aerosol mass (Wagenbach et al., 1998). The NaCl mass concentration in Antarctica varies with the season and airmass origin. Giordano et al. (2018) demonstrated that NaCl concentrations are pronounced in the continental Antarctic airmasses, suggesting a threshold windspeed of 6 – 10 m s⁻¹ for SSA production from drifting snow. They also found that NaCl mass concentrations at McMurdo Station are roughly 10 times higher during the stormy spring than summer.

A direct connection between snow, wind and SSA was established recently when Frey et al. (2020) provided the first direct observations of SSA production from the sublimating snow particles during blowing snow episodes over the Weddell Sea ice, Antarctica. The threshold windspeed for SSA production was around 8 m s⁻¹. Their observation, hypothesized already earlier (e.g. Giordano et al., 2018; Yang et al., 2008), largely filled the gap in understanding the SSA production in the Antarctic and Arctic domain, which was highly underestimated by the models that only account for sea spray as a source of SSA (Huang and Jaeglé, 2017). Frey et al. (2020) also observed a connection between the snow salinity and produced aerosol size distributions consistent with model predictions (Yang et al., 2019). They also found that SSA particle number and mass



concentrations produced by snowstorms can exceed those produced by the storm over the open ocean (Frey et al., 2020). Since SSA is the primary component in marine and polar aerosol mass, blowing snow events and snowstorms likely have significant effects in regional aerosol and CCN loads. Moreover, because SSA particles contain not only sodium chloride, but also species such as bromine, the produced aerosol can contribute to the atmospheric bromine budget and, in turn, to ozone depletion and atmospheric chemistry more broadly (e.g. Huang et al., 2020; Jones et al., 2009).

More recently, Gong et al. (2023) measured snowstorm-generated SSA production in wintertime central Arctic, finding that blizzard generated aerosol accounts for almost 30% of total aerosol concentration. They also reported a significant positive radiative effect of these particles via increased longwave emissivity of low-level clouds.

In the present work, we studied the formation of ion clusters (0.8 – 2 nm) and charged particles (up to 40 nm in diameter) from blowing snow with specific aims to i) resolve the chemical composition of the small ions and ii) the dependency of ion size, composition and concentration on wind speed and iii) to discuss the potential impact of storm generated ions on atmospheric aerosol and CCN formation.

2 Methods

We conducted our experiments during a field campaign at the German Alfred Wegener Institute's Neumayer III station in Queen Maud Land, Antarctica from 17 November 2018 until 7 February 2019. The station is located on the Ekström ice shelf approximately 8 km from the Southern Ocean and the Atka Bay, which was covered by sea ice throughout the whole campaign. Most of the instrumentation we used for this work was located in a measurement container on the snowpack, 1.5 km south of the Neumayer main station, next to the Air Chemistry Observatory (Spurenstoff-Observatorium, SPUSO). Air samples were taken through the container wall facing North at approximately 2 m above the ground. The meteorological data was collected at the Neumayer official GAW weather station.

We used a Neutral cluster and Air Ion Spectrometer (NAIS, Manninen et al., 2009; Mirme and Mirme, 2013) for the detection of the ion mobility equivalent diameter distribution between 0.8 and 40 nm. For spherical, singly charged particles, mobility equivalent diameter differs from geometrical “true” diameter by ca. 0.3 nm, which is the approximate diameter of colliding air molecules, with the geometrical diameter being smaller. The NAIS sampling was performed through a 1 m long i.d. 35 mm copper tube with the flow rate of 54 lpm. The used sampling configuration minimizes diffusion losses – theoretical ion penetration for smallest, mobility diameter of 0.8 nm ions is >90%. Between 17 November and 1 December 2018, one of the electrometers of the NAIS was malfunctioning, and the negative ion concentrations in the size range of 2.2 – 2.6 nm were not measured correctly.



For detecting the ion composition, we used an Atmospheric Pressure interface Time-of-Flight mass spectrometer (APi-TOF, ToFwerk A.G., Switzerland, Junninen et al., 2010) without chemical ionization or any sample pre-treatment. The APi-TOF was configured for detection of ions in the mass range of ca. 50 – 800 Da, which correspond to mobility diameter range of ca. 0.7 – 1.4 nm. The sensitivity of the APi-TOF is best for ions around 200-300 Da, and drops with increasing or decreasing mass. Therefore, the reported signal intensities between different ions are not directly comparable. The sampling was performed with a 1 m long i.d. 10 mm stainless steel tube with 10 lpm sample flow rate out of which 0.7 lpm was extracted for analysis at the APi-TOF entrance pinhole plate. The diffusion losses for 0.8 nm / 100 Da ions in used configuration are ca. 50%. The APi-TOF was mostly operated in negative ion mode and occasionally in positive ion mode. However, we failed to calibrate the mass-axis in the positive mode. Therefore, the data from positive ions could not be included in the further analysis. Both NAIS and APi-TOF were located in the measurement container.

The particle size distribution of 6 – 220 nm was measured at the Air Chemistry Observatory by a Scanning Mobility Particle Sizer (SMPS; Wang and Flagan, 1990). The SMPS's mobility classifier (TSI classifier model 3080) comprised of a DMA (differential mobility analyser, TSI Model 3081) preceded by a soft X-ray diffusion charger (TSI Model 3088; Tigges et al., 2015) and a condensation particle counter (TSI model CPC 3776) with a 50% cut-off diameter of 2.5 nm. All size spectra were multiple charge and diffusion corrected according to the TSI software AIM (Aerosol Instrument Manager®). The SMPS sample was taken via vertical inlet from 7 m height. The inlet was equipped with a PM-10 impactor and a dryer.

Besides the official meteorological station, we conducted meteorological measurements at the measurement container. A comparison between the meteorological variables at the container and at the meteorological station showed, that the wind speed at 10 m height measured at the meteorological station agreed well with the wind speed recorded at the container (5m (above ground) (Fig. S1). Therefore, for further analysis, we used the official measurements at the Neumayer weather station.

3 Results and discussion

3.1 Ion concentration and meteorological conditions

During the measurement campaign, we detected several episodes with a high ion concentration, as can be seen from the ion size distribution of negative and positive ions in Fig. 1 B & C. Aerosol particles with diameters of > 6 nm recorded by the SMPS did not show the same pattern as the ions (Fig. 1 A). Each event of high ion concentration is associated with wind speeds exceeding 8 m s⁻¹ (indicated with a red line) as well as very low visibility (Fig. 1 D) which proxies the flying snow. With wind speeds higher than 8 m s⁻¹, the ion (0.8 – 40 nm mobility equivalent diameter) concentration rapidly increases by two orders of magnitudes. It should be noted that NAIS data inversion routine concentration calculation cannot not account for multiply charging of ions which may slightly affect the reported concentrations.

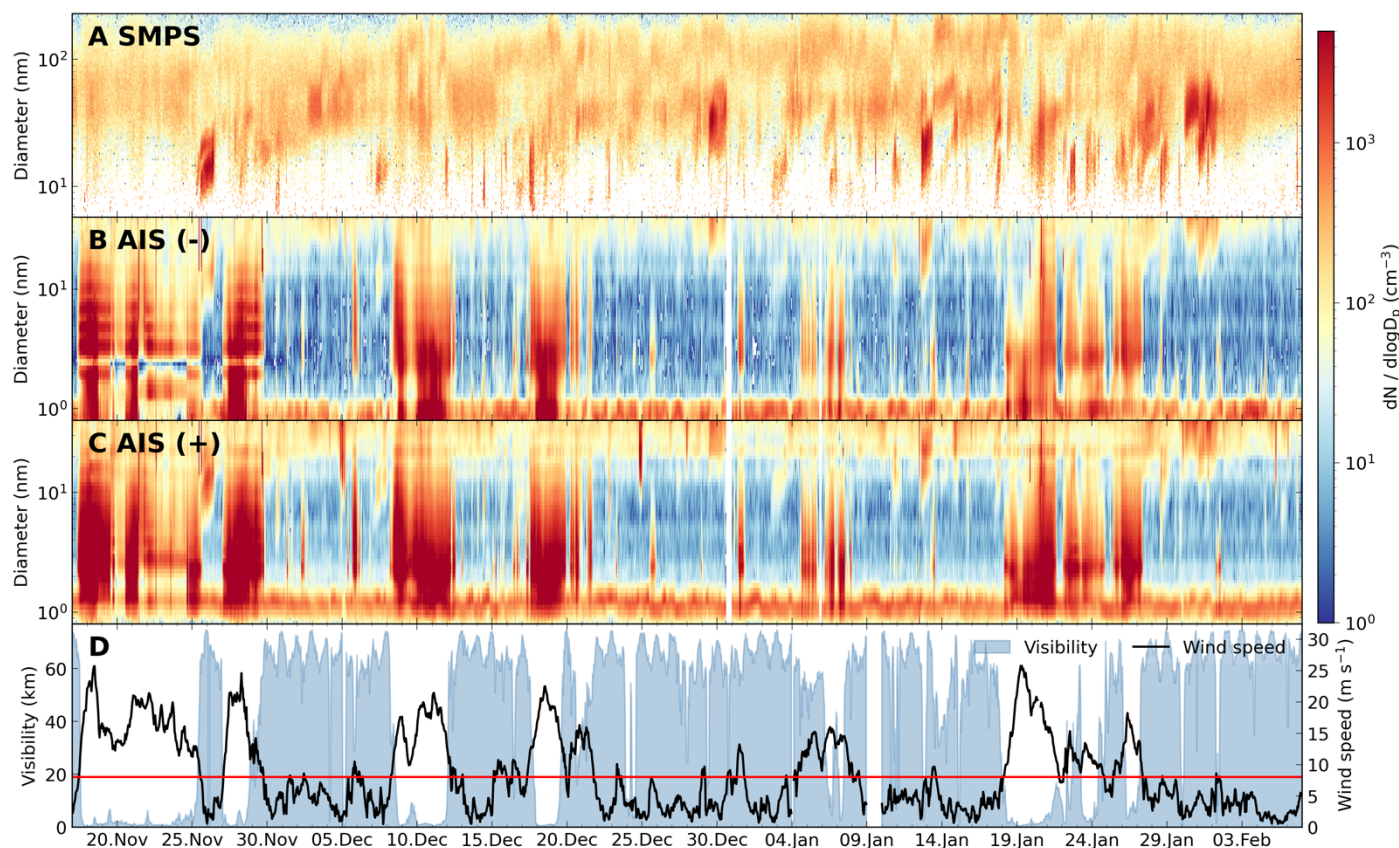


Figure 1: Particle size distribution of particles with a diameter 6 - 220 nm (A) measured with SMPS. Negative (B) and positive (C) ion size distribution with a diameter of 0.8 - 40 nm. Visibility (blue shaded) and wind speed (black) (D). The red line is indicating wind speeds of more than 8 m s⁻¹ when the ion concentration rapidly increases and the visibility drops. The depicted period is 17 November 2018 to 7 February 2019. Between 17 November and 01 December 2018, one channel of the negative ions was malfunctioning.

Figure 2 shows the average size distributions for time period from 17 Nov to 7 Feb for both instruments during calm weather with wind speed of 0-8 m s⁻¹, during moderate wind speed of 8-18 m s⁻¹ and during blizzards with wind speed exceeding > 18 m s⁻¹. Ion size distributions are strongly affected by the wind with ion concentrations increasing by 1-2 orders of magnitude depending on ion size, from calm weather to blizzard conditions.

Size distribution and total concentration of particles measured by SMPS is not, however, distinctly affected by the wind (Figure 2). The shape of the number size distribution (5 nm to ca. 20 nm) measured by SMPS also does not match the shape of the number size distribution of ions measured by NAIS. A similar observation was made by Chen et al. (2017), who did not discuss the reasons for the difference, and Virkkula et al. (2007), who concluded that the used DMPS system (mechanically similar to SMPS, but differently configured measurement cycle) for some reason cannot detect the smallest particles. DMPS/SMPS

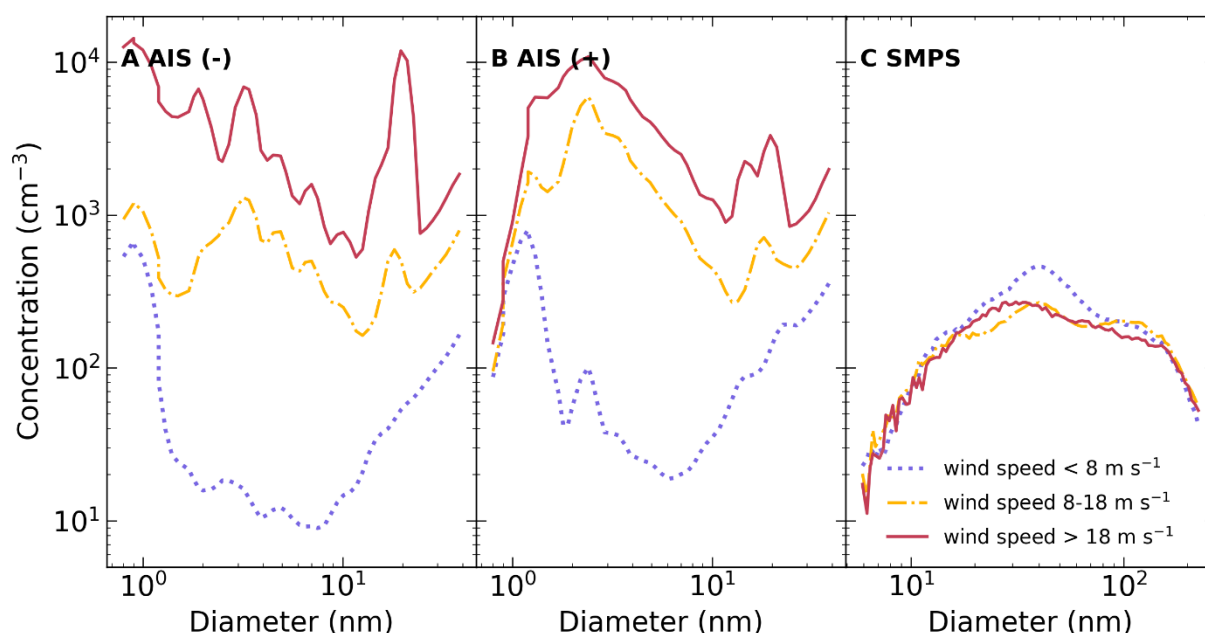


Figure 2: Average size distribution of negative ions, positive ions and neutral particles during fair weather conditions (wind speed < 6 m s⁻¹), wind speeds of 8 to 18 m s⁻¹ and blowing snow conditions with wind speeds > 18 m s⁻¹ shown for (A) AIS in negative mode, (B) AIS in positive mode and (C) SMPS.

While the performance of the SMPS used in this study has not been evaluated for sub-20 nm particles of interest, we can discuss the detection process in general to point out possible reasons for the missing signal specifically in our case. In the SMPS, aerosol is neutralized, i.e. brought to charge equilibrium (Tigges et al., 2015; Wiedensohler et al., 1986) with a bi-polar neutralizer, before particle size classification. Ions (which are readily observed by NAIS) mostly lose their charge in the neutralization process and therefore a direct comparison is not even meaningful. If most of the wind generated particles are charged, they are observed by the NAIS but appear less pronounced in the SMPS. The SMPS can, consequently, be less sensitive than the NAIS for charged nanoparticles (see Figure S2 for particle mode measured by NAIS). A fraction of the particles observed by the NAIS can also be multiply charged, which causes the detected electrical mobility diameters to be significantly smaller than the actual mobility diameters. In contrast, the SMPS output is not affected by the number of elementary charges. The SMPS sampling tube was also located ca. 7 m above the snow surface and thus above the layer of intensively blowing snow. The particles produced in the snowstorm are naturally more concentrated within the blizzard than above it and are probably also, to some extent, scavenged by snow/ice crystals and flakes, which decreases their probability of reaching the layer above the blizzard. Furthermore, the small particles produced within the blizzard may have non-negligible



evaporation rates and while during NAIS and APi-TOF sampling the particles are detected promptly after separated from the ambient air without drying or heating, the SMPS sampling involves sample drying (removing the stabilizing water from the clusters), neutralization (removing charge from most particles, which may be necessary for the stability of small few nm clusters) and size separation in DMA operated in dried and warmed-up air which may further destabilize the nanoscale particles and clusters. Besides unknown technical reasons often deteriorating the sensitivity of SMPS systems in general, it could therefore be possible that some or most of the particles in the nanometre-range evaporate before being counted by the CPC used as a detector in the SMPS.

Despite the above discussed possible but unconfirmed reasons for SMPS's blindness to small, charged particles, it could be hypothesized that NAIS measurement is affected by the storm. However, an independent ion detector, the APi-TOF mass spectrometer, confirms the presence of charged clusters and validates the NAIS measurement during storms (next chapter).

To gain deeper insights into the relationship between ion concentration and wind speed and to resolve the chemical composition of ions, we investigated a single storm event described in detail in the following paragraphs.

3.2 Case study

On 27 and 28 November, a low-pressure cell was causing high easterly wind speeds reaching 25 m s^{-1} with wind gusts up to 33 m s^{-1} (Fig. 3 C). During this event, high concentrations of $0.8\text{-}2 \text{ nm}$ ions – up to $2 \cdot 10^4 \text{ cm}^{-3}$ negative and $7 \cdot 10^3 \text{ cm}^{-3}$ positive as recorded by NAIS – were observed (Fig. 3 C, E & F). The ion concentration recorded by NAIS started to increase when the wind speed exceeded $6\text{-}10 \text{ m s}^{-1}$ (Fig. 3 C, E & F and Fig. 4) with reaching 'apparent' concentrations of up to $2 \cdot 10^4 \text{ cm}^{-3} / 7 \cdot 10^3 \text{ cm}^{-3}$ (negative/positive) at wind speed of 25 m s^{-1} . However, the particle concentration measured with the SMPS shows no clear response to the increasing wind speeds (Fig. 3 D), and the total concentration varied between 90 and 1000 cm^{-3} .

When the wind speed increased above 18 m s^{-1} , very small ($<800 \text{ Th}$) negative sodium chloride ions $(\text{NaCl})\text{Cl}^-$ appeared with concentrations sufficient to be detected by the APi-TOF (Fig. 3 A&B). Minor signals appear in the APi-TOF already in the morning hours on 27 November around 3:00 UTC for a brief time, coinciding with elevated concentration of small ions with diameters of $0.8 - 2 \text{ nm}$ recorded by NAIS. Eye-catching is that the signals of $(\text{NaCl})_{(x)}\text{Cl}^-$ ions increase rapidly from no signal in the APi-TOF to several ions per second when the wind speed exceeds 18 m s^{-1} at ca. 10:30 UTC. Concurrently, the negative $0.8 - 2 \text{ nm}$ cluster ion signal measured by NAIS increases, reaching ca. $2 \cdot 10^4 \text{ cm}^{-3}$ with the wind speed of 25 m s^{-1} following the APi-TOF signals. Positive $0.8 - 2 \text{ nm}$ cluster ion signal show a less predominant increase and no clear threshold at 18 m s^{-1} wind speed as negative cluster ions. Still, a positive ion concentration of $7 \cdot 10^3 \text{ cm}^{-3}$, ca. 50-fold to that preceding the storm, is reached with the wind speed of 25 m s^{-1} .

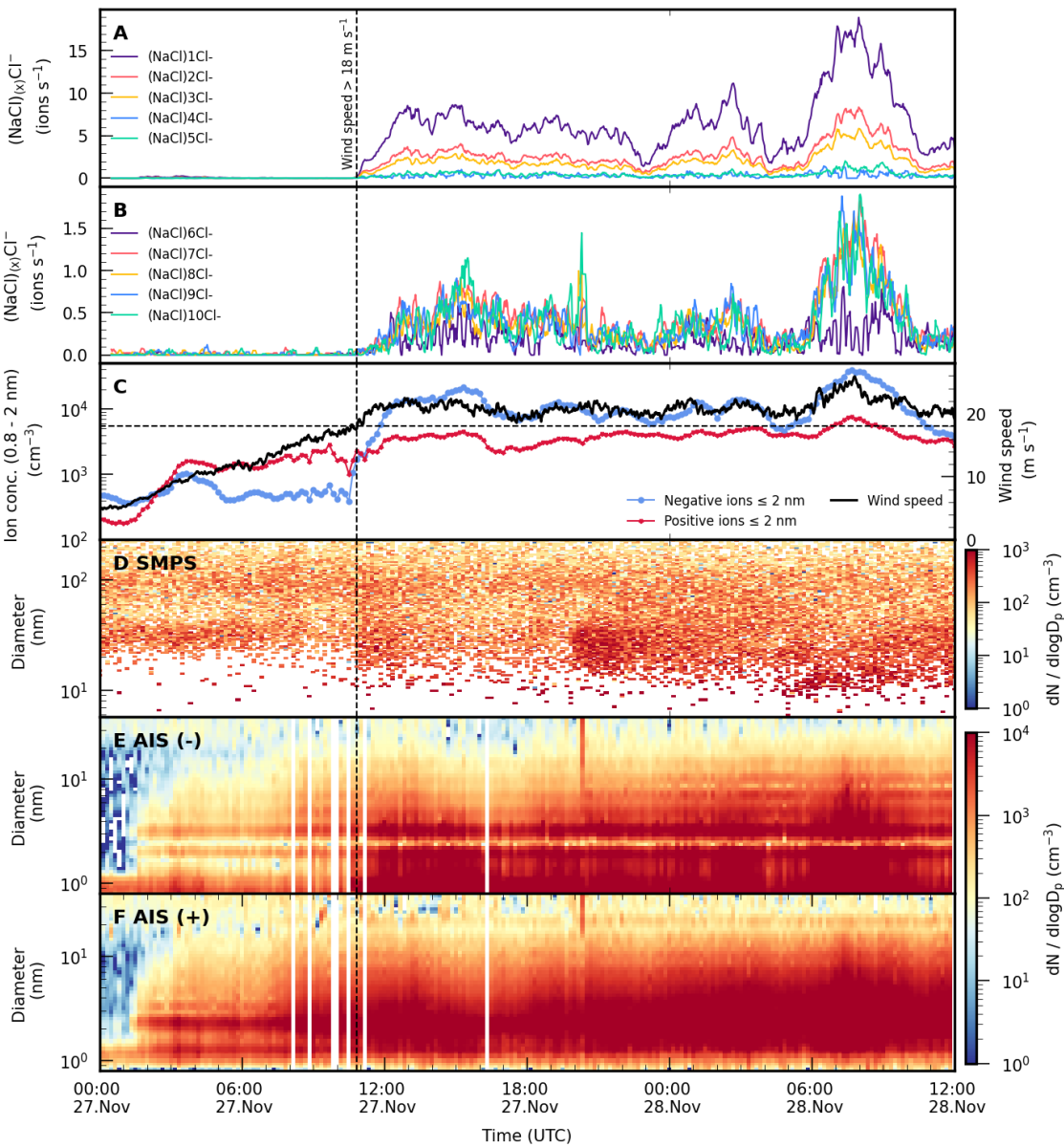


Figure 3: Ion and aerosol data recorded from 27 November to 28 November 12 UTC. (A and B) Time series of sodium chloride cluster ion signals recorded with API-TOF mass spectrometer with two different y-axis scales. **(C)** Sum of negative and positive ions in the size range of 0.8 to 2 nm, recorded by air ion spectrometer (NAIS) together with the wind speed. **(D)** Particle size distribution (6-220 nm) measured with SMPS. **(E)** Negative ion size distribution (0.8 – 40 nm). **(F)** Same as in E but for positive ions. The dashed line indicates when the wind speed exceeds 18 m s⁻¹.

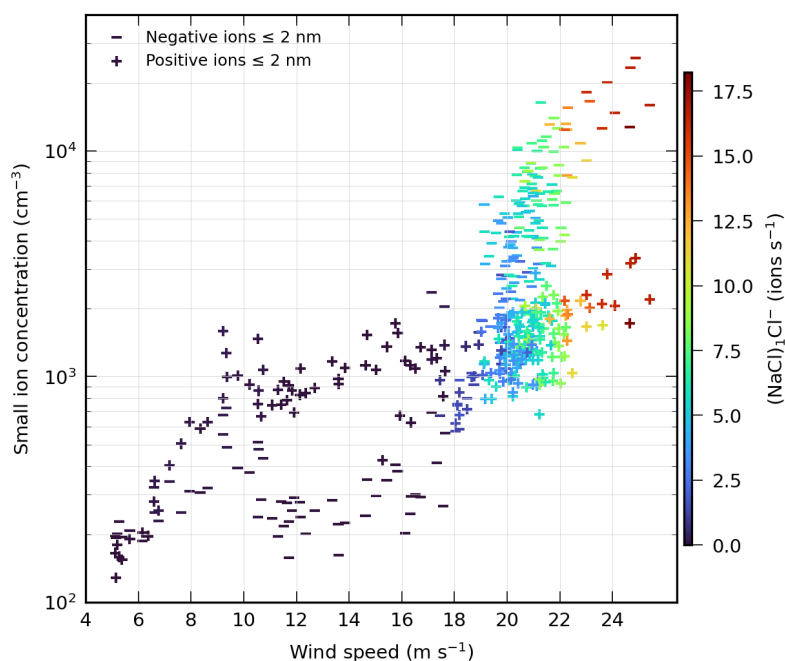


Figure 4: Small ion concentration measured by NAIS and wind speed on 27 and 28 of November. The color indicates the APi-TOF mass spectrometer signal of the $(\text{NaCl})_1\text{Cl}^-$ ion.

The mass spectrum recorded by APi-TOF during high wind speed (on 27 November 2018 12:00 – 15:00 UTC) shows a specific pattern (Fig. 5) and a total ion count of 2 - 20 counts per second. Further analysis showed that those ions contain NaCl complexes clustered with several kinds of ions. The strongest signals in the mass spectrum (shown in blue in Fig. 5) are associated with NaCl complexes clustered with a Cl^- ion: $(\text{NaCl})_x\text{Cl}^-$, with $x = 1:11$ while the rest of the signal mostly consists of multiply charged $(\text{NaCl})_x\text{n}(\text{Cl}^-)$ -clusters, $(\text{NaCl})_x$ -clusters with a core ion other than Cl^- , including MnO^- (Fig. 5, shown in red), and/or $(\text{NaCl})_x\text{Cl}^-$ -clusters with known/unknown compounds.

Most of the mass within unidentified clusters, i.e. clusters with unknown compounds, is most likely also due to NaCl. But how do we know that? Figure 6 depicts the mass spectrum by means of a mass defect plot. In contrast to elementary physics (where the mass defect is defined as the difference between the mass and the sum mass of individual nucleons), in atmospheric mass spectrometry applications the mass defect is usually defined as the difference between the ion-cluster mass in Th ($1 \text{ Th} = 1 \text{ Da} = 1 \text{ u}$) and the sum number of nucleons in the atomic nuclei of that ion. I.e. C-12, which weighs exactly 12 Da (or 12 u), has a mass defect of zero. In line with the usual visual representation and because we do not know the sum concentrations of nucleons for all peaks in the spectrum, we define the mass defect as the difference between cluster m/z value and the nearest integer m/z value. Therefore, the mass defect in our case gets only values between -0.5 and +0.5 Th and true defects below -0.5 Th appear in figure as positive defects. It is evident from Figure 6 that the signal, or peaks in the spectrum, fall on a line with a slope



$\Delta(\text{mass defect}) / \Delta(\text{mass/charge})$ which equals to that of NaCl: $-7.14 \cdot 10^{-5}$ Th/Th (Fig. 6). This observation leads to the conclusion that mostly all ions should contain a variable number of NaCl complexes on top of the core ion as well. Therefore, most of the mass associated with these small ions, is also due to NaCl.

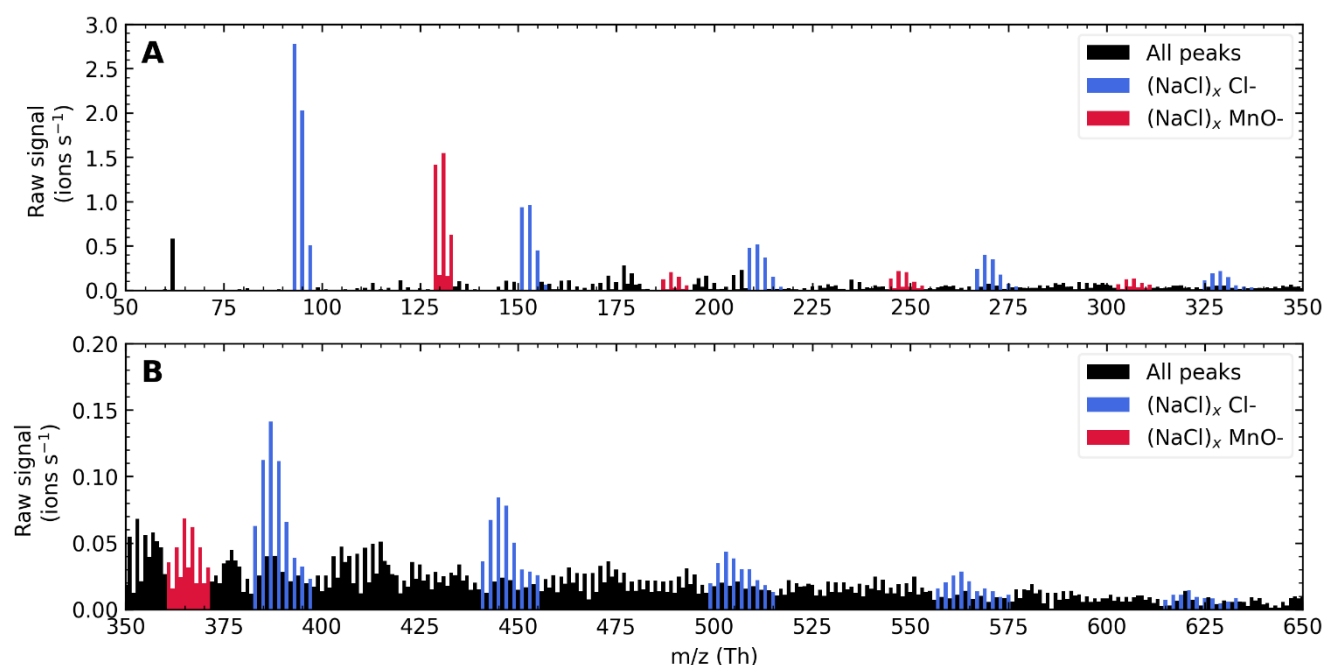


Figure 5: Mass spectrum of negative ions during blowing snow event on 28th of November 05 - 14 UTC. The colored bars are pure sodium chloride clusters $(\text{NaCl})_x$ together with the chloride ion Cl^- (blue) or MnO^- -ion (red). Black bars are mostly multiply charged $(\text{NaCl})_x$ clusters, $(\text{NaCl})_x$ clusters with core ion other than Cl^- or MnO^- and/or $(\text{NaCl})_x \text{Cl}^-$ -clusters with known/unknown impurities. For clarity, the continuous mass spectrum is represented as distinct bars centralized around integer m/z values.

Besides the predominant Cl^- -ion, we were able to identify 11 additional ions clustering with NaCl, including halogens such as I^- , IO_3^- , alkali compounds NaO^- , NaO_2^- , common atmospheric air ions SO_3^- , HSO_4^- , NO_3^- , O_2^- , as well as MnO^- , CaCl^- and HS^- . Still, there are many more ions unidentified, but the slope of the mass defect of NaCl (Fig. 6) shows that they at least contain NaCl and only differ by their core ion. For ions heavier than ca. 680 Th the mass defect exceeds -0.5 Th, leading to their appearance on the positive side of the mass defect.

The negative 0.8-2nm ion concentration measured by NAIS is correlating well with the signal of NaCl containing ions recorded by APi-TOF during high wind speed (Figs. 3 & 4). This relationship together with unambiguous identification of cluster composition indicates that a vast amount of those small negative ion clusters detected with the NAIS are NaCl clusters. While the NAIS detects ion production already at wind speeds above 8 m s^{-1} , small negative ions are detected with the APi-TOF only with wind speeds above 18 m s^{-1} when the concentrations of different ions with certain composition get sufficiently high for exceeding the detection threshold of the APi-TOF. As can be seen from Fig. 3 C and Fig. 4, negative ion concentration in the



APi-TOFs detection window of 0.8 – ca. 2 nm (mobility equivalent diameter) increases by an order of magnitude from the wind speed range 8–18 m s⁻¹ to wind speeds of more than 18 m s⁻¹. Similar observations were made also during other snowstorm episodes (Fig. S3 & S4).

Since the negative ion count is increasing during high wind speeds, we also tried to measure the composition of positive ions and switched the mode of APi-TOF from negative to positive. The total ion current during the snow storm (wind speed > 18 m s⁻¹) was 20 to 30 ions s⁻¹, comparable to that of negative suggesting strong positive small (< 800 Th) ion production as well in line with the NAIS ion observations (Fig. 1 C and Fig. 3 C&F). Unfortunately, the instrument mass calibration in positive ion mode had shifted and we were not able to reconstruct the m/z-spectrum from the time-of-flight spectrum. Conversion of time-of-flight spectrum to m/z-spectrum would require knowledge on atomic composition of at least two properly separated peaks in the spectrum. Several attempts to identify peaks we would expect to see, such as (NaCl)_xNa⁺ failed. This also suggests that positive spectrum likely is more complex, with more variation in chemical composition and pure (NaCl)_xNa⁺-clusters are not as dominant as their negative counterparts (NaCl)_xCl⁻.

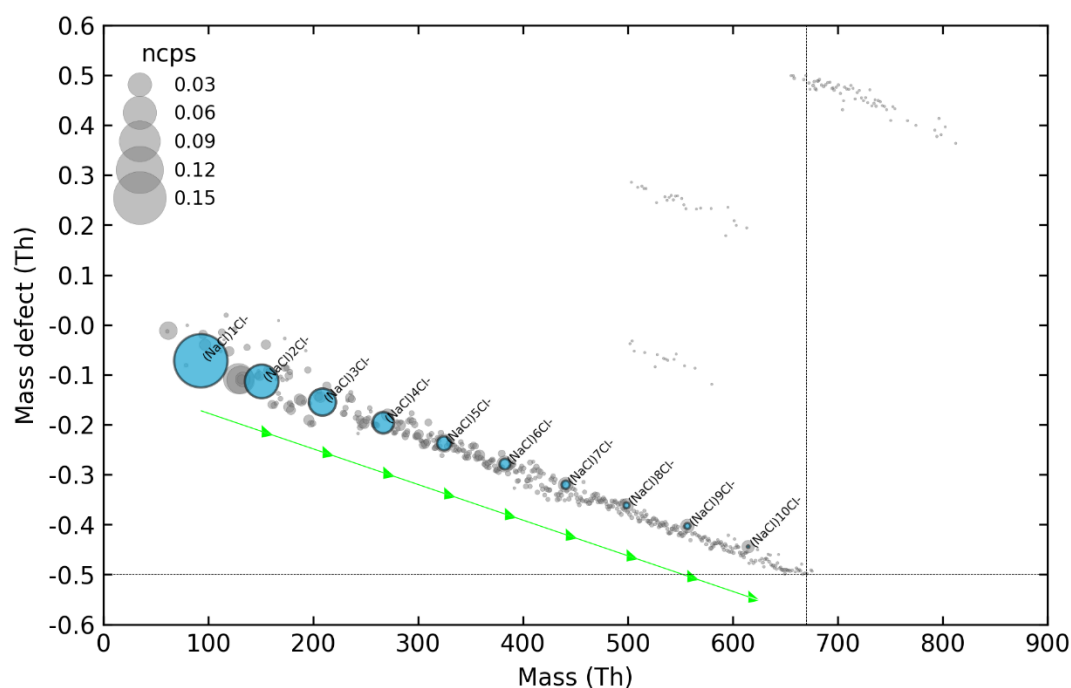


Figure 6: Mass defect plot of negative ions during blowing snow event on 28 November 2018, 06:00 – 11:00 UTC. All coloured dots show sodium chloride clusters (NaCl)_(x) together with a Chloride (Cl⁻ ion). The size of the markers shows the normalized counts per second (ncps) as depicted in the legend.

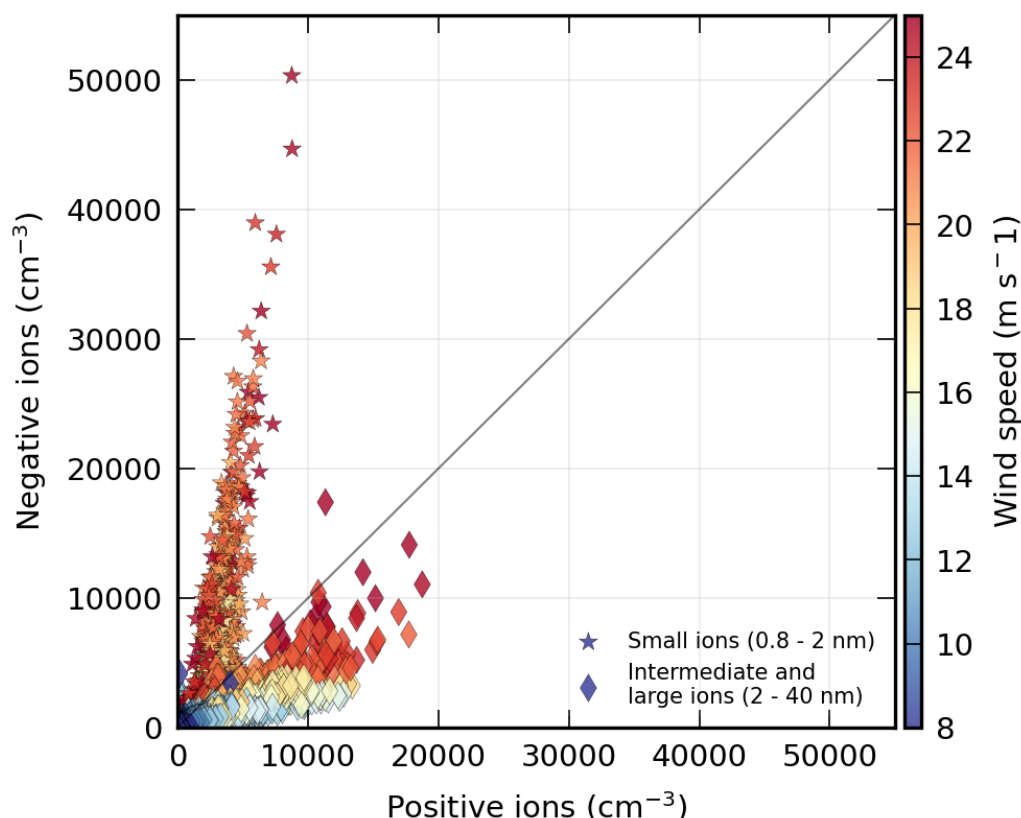


Figure 7: Positive versus negative ions divided into size groups of small ions (0.8 – 2 nm) and intermediate and large ions (2-40 nm). The colouration is indicating the wind speed in m s⁻¹. With wind speeds exceeding 18 m s⁻¹, the majority of small ions is negative, while the majority of larger ions is positive.

3.3 Overall observation of ion concentration

The behaviour of positive versus negative ions is very different during higher wind speeds. The concentration of positive ion clusters (0.8 – 2 nm) during blowing snow events does not seem to respond to slight wind speed changes as dramatically as negative ion clusters (Fig. 3C). Additionally, the small ions between 0.8 and 2 nm react differently than the larger ones. Figure 7 shows that high wind speeds produce 3-5 times higher apparent concentration of small negative clusters than positive ones, while the apparent concentration of the intermediate and larger ions (2-40 nm), on the other hand, is higher in the positive channel. This imbalance may have been observed also in preceding studies by Chen et al. (2017), Manninen et al. (2010) and Virkkula et al. (2007) where similar instruments, NAIS or AIS, were used. Unfortunately, none of these studies report ion size distributions of both polarities. The reason behind the different behaviour of negative and positive clusters should be related to detailed ion production mechanisms (discussed in the Introduction) resulting in either smaller physical size of negative ions



or in higher relative concentration of multiply charged negative ions, in which case the electrical mobility diameters of negative ions would be naturally smaller. Because most of the negative ions identified by APi-TOF were singly charged, the latter explanation is not feasible. Both negative and positive ion clusters are very small and likely produced in a chain of processes (see Introduction) and thus any cloud relevant processes that explain the size dependent charge separation between graupels and ice crystals cannot explain our observations but the reasons for the observed imbalance remains open.

4 Conclusions

We have shown that electric field observed in Antarctic snowstorms during Scott's expedition (Simpson, 1921) and in numerous follow up studies is caused by air ions predominantly composed of NaCl. Our study also adds to the earlier work by Virkkula et al. (2007) and Chen et al. (2017) where ion production associated with elevated wind speed and blowing snow was observed, but without information on the chemical nature of the detected ions.

During snowstorms, the concentration of negative and positive ion clusters in the size range from 0.8 to 2 nm can temporarily reach several 10^4 cm^{-3} or several 10^3 cm^{-3} , respectively. Concentrations of intermediate ions/charged particles (2-7 nm) reach ca. $2 \cdot 10^4 \text{ cm}^{-3}$ (negative) and ca. $3 \cdot 10^4 \text{ cm}^{-3}$ (positive). These concentrations are clearly higher than the few 10^3 cm^{-3} total particle (charged + neutral) concentrations observed during new particle formation events (Jokinen et al., 2018) believed to have a major contribution to Antarctic CCN budget. However, highly concentrated ion clusters rapidly recombine forming neutral clusters and particles. Charge may be very important for cluster stability, and it is uncertain how stable neutral NaCl clusters are against evaporation. Besides neutral particles, also small charged NaCl clusters may evaporate resulting in a highly mobile core ion which is rapidly scavenged by existing aerosol or snow crystal. We could not see any clear increase in $> 6 \text{ nm}$ particle concentration measured by SMPS above the snow blizzard. This may be due to instrumental problems or sample drying and neutralization preceding the detection, but also a real indication on the short lifetime of 6-40 nm charged particles observed by NAIS.

Even though very high concentrations of charged NaCl clusters and particles were observed within the flying snow, further investigations on the stability and lifetime of these particles, as well as their distribution outside the intensive blizzard are required before conclusions regarding the relevance of the process to larger scale aerosol and CCN concentrations can be drawn.

Author contributions

LJB and MS designed the field campaign. TL assisted with campaign preparations and setup/build the measurement container. LJB, MS and RW performed the field studies. LJB performed the data analysis. LJB, MS and RW wrote the paper. All authors contributed to discussions and commented on the paper.



365

366 **Competing interests**

367 Authors declare no competing interests.

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369 **Data availability**

370 Data will be submitted to Zenodo upon publication of manuscript in ACP, until that data is available on request.

371

372 **Acknowledgements**

373 Finnish Antarctic research program (FINNARP) is acknowledged for advising and logistical support between Finland and
374 Cape Town. Alfred Wegener Institute and staff at Neumayer III are acknowledged for providing the access to Neumayer III
375 station, technical assistance during the campaign and organizing the logistics. Tuukka Petäjä and INAR staff are acknowledged
376 for useful discussions and support with the campaign.

377

378 **Financial support**

379 Financial support from Academy of Finland (projects: 296628, 328290, 335844, 337549, 302958), the European Research
380 Council (ERC) under the European Union's Horizon 2020 research and innovation programme (GASPARCON, grant
381 agreement no. 714621) and Estonian Research Council (project PRG714) are acknowledged.

References

- Asmi, E., Sipilä, M., Manninen, H. E., Vanhanen, J., Lehtipalo, K., Gagné, S., Neitola, K., Mirme, A., Mirme, S., Tamm, E., Uin, J., Komsaare, K., Attoui, M., and Kulmala, M.: Results of the first air ion spectrometer calibration and intercomparison workshop, *Atmospheric Chemistry and Physics*, 9, 141–154, <https://doi.org/10.5194/acp-9-141-2009>, 2009.
- Beck, L. J., Sarnela, N., Junninen, H., Hoppe, C. J. M., Garmash, O., Bianchi, F., Riva, M., Rose, C., Peräkylä, O., Wimmer, D., Kausiala, O., Jokinen, T., Ahonen, L., Mikkilä, J., Hakala, J., He, X.-C., Kontkanen, J., Wolf, K. K. E., Cappelletti, D., Mazzola, M., Traversi, R., Petroselli, C., Viola, A. P., Vitale, V., Lange, R., Massling, A., Nøjgaard, J. K., Krejci, R., Karlsson, L., Zieger, P., Jang, S., Lee, K., Vakkari, V., Lampilahti, J., Thakur, R. C., Leino, K., Kangasluoma, J., Duplissy, E.-M., Siivola, E., Marbouti, M., Tham, Y. J., Saiz-Lopez, A., Petäjä, T., Ehn, M., Worsnop, D. R., Skov, H., Kulmala, M., Kerminen, V.-M., and Sipilä, M.: Differing Mechanisms of New Particle Formation at Two Arctic Sites, *Geophysical Research Letters*, 48, e2020GL091334, <https://doi.org/10.1029/2020GL091334>, 2021.
- Boyer, M., Quéléver, L., Brasseur, Z., McManus, B., Herndon, S., Agnese, M., Nelson, D., Roscioli, J., Weis, F., Sel, S., Marincovich, G.L., Quarin, F.J., Buchholz, A., Xavier, C., Perchivale, P.J., Kerminen, V.-M., Kulmala, M., Petäjä, T., He, X.-C., Sofieva-Rios, S., Timonen, H., Aurela, M., Barreira, L., Virkkula, A., Asmi, E., Worsnop, D., Sipilä, M.: Penguin guano is an important source of climate-relevant aerosol particles in Antarctica, *Communications Earth & Environment* 6, 368, <https://doi.org/10.1038/s43247-025-02312-2>, 2025



Chen, X., Virkkula, A., Kerminen, V.-M., Manninen, H. E., Busetto, M., Lanconelli, C., Lupi, A., Vitale, V., Del Guasta, M., Grigioni, P., Väänänen, R., Duplissy, E.-M., Petäjä, T., and Kulmala, M.: Features in air ions measured by an air ion spectrometer (AIS) at Dome C, *Atmospheric Chemistry and Physics*, 17, 13783–13800, <https://doi.org/10.5194/acp-17-13783-2017>, 2017.

Drake, J. C.: Electrification accompanying the melting of ice particles, *Quarterly Journal of the Royal Meteorological Society*, 94, 176–191, <https://doi.org/10.1002/qj.49709440007>, 1968.

Fraser, M. M. and Beauchemin, D.: Evidence supporting the occurrence of Coulomb fission during conventional sample introduction in inductively coupled plasma mass spectrometry, *J. Anal. At. Spectrom.*, 24, 469–475, <https://doi.org/10.1039/B819816K>, 2009.

Frey, M. M., Norris, S. J., Brooks, I. M., Anderson, P. S., Nishimura, K., Yang, X., Jones, A. E., Nerentorp Mastromonaco, M. G., Jones, D. H., and Wolff, E. W.: First direct observation of sea salt aerosol production from blowing snow above sea ice, *Atmospheric Chemistry and Physics*, 20, 2549–2578, <https://doi.org/10.5194/acp-20-2549-2020>, 2020.

Giordano, M. R., Kalnajs, L. E., Goetz, J. D., Avery, A. M., Katz, E., May, N. W., Leemon, A., Mattson, C., Pratt, K. A., and DeCarlo, P. F.: The importance of blowing snow to halogen-containing aerosol in coastal Antarctica: influence of source region versus wind speed, *Atmospheric Chemistry and Physics*, 18, 16689–16711, <https://doi.org/10.5194/acp-18-16689-2018>, 2018.

Gong, X., Zhang, J., Croft, B., Yang, X., Frey, M. M., Bergner, N., Chang, R. Y.-W., Creamean, J. M., Kuang, C., Martin, R. V., Ranjithkumar, A., Sedlacek, A. J., Uin, J., Willmes, S., Zawadowicz, M. A., Pierce, J. R., Shupe, M. D., Schmale, J., and Wang, J.: Arctic warming by abundant fine sea salt aerosols from blowing snow, *Nat. Geosci.*, 16, 768–774, <https://doi.org/10.1038/s41561-023-01254-8>, 2023.

Gordon, H., Kirkby, J., Baltensperger, U., Bianchi, F., Breitenlechner, M., Curtius, J., Dias, A., Dommen, J., Donahue, N. M., Dunne, E. M., Duplissy, J., Ehrhart, S., Flagan, R. C., Frege, C., Fuchs, C., Hansel, A., Hoyle, C. R., Kulmala, M., Kürten, A., Lehtipalo, K., Makhmutov, V., Molteni, U., Rissanen, M. P., Stozkhov, Y., Tröstl, J., Tsagkogeorgas, G., Wagner, R., Williamson, C., Wimmer, D., Winkler, P. M., Yan, C., and Carslaw, K. S.: Causes and importance of new particle formation in the present-day and preindustrial atmospheres, *Journal of Geophysical Research: Atmospheres*, 122, 8739–8760, <https://doi.org/10.1002/2017JD026844>, 2017.

Gormley P. G. and Kennedy M., Diffusion from a Stream Flowing through a Cylindrical Tube, *Proceedings of the Royal Irish Academy. Section A: Mathematical and Physical Sciences*, 52, (1948-1950), pp. 163-169.

Gross, G. W.: The Workman-Reynolds effect and ionic transfer processes at the ice-solution interface, *Journal of Geophysical Research* (1896-1977), 70, 2291–2300, <https://doi.org/10.1029/JZ070i010p02291>, 1965.

Hallett, J. and Saunders, C. P. R.: Charge Separation Associated with Secondary Ice Crystal Production, *Journal of the Atmospheric Sciences*, 36, 2230–2235, [https://doi.org/10.1175/1520-0469\(1979\)036<2230:CSAWSI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1979)036<2230:CSAWSI>2.0.CO;2), 1979.



Harris, C. and Stace, A. J.: Coulomb Fission in Multiply-Charged Ammonia Clusters: Accurate Measurements of the Rayleigh Instability Limit from Fragmentation Patterns, *The Journal of Physical Chemistry A*, 122, 2634–2644, <https://doi.org/10.1021/acs.jpca.8b00815>, 2018.

Haymet, A. D. J. and Wilson, P. W.: The Workman–Reynolds “Freezing Potential”: A new look at the inherent physical process, *Journal of Molecular Liquids*, 228, 243–246, <https://doi.org/10.1016/j.molliq.2016.07.081>, 2017.

He, X.-C., Tham, Y. J., Dada, L., Wang, M., Finkenzeller, H., Stolzenburg, D., Iyer, S., Simon, M., Kürten, A., Shen, J., Rörup, B., Rissanen, M., Schobesberger, S., Baalbaki, R., Wang, D. S., Koenig, T. K., Jokinen, T., Sarnela, N., Beck, L. J., Almeida, J., Amanatidis, S., Amorim, A., Ataei, F., Baccarini, A., Bertozzi, B., Bianchi, F., Brilke, S., Caudillo, L., Chen, D., Chiu, R., Chu, B., Dias, A., Ding, A., Dommen, J., Duplissy, J., El Haddad, I., Gonzalez Carracedo, L., Granzin, M., Hansel, A., Heinritzi, M., Hofbauer, V., Junninen, H., Kangasluoma, J., Kemppainen, D., Kim, C., Kong, W., Krechmer, J. E., Kvashin, A., Laitinen, T., Lamkaddam, H., Lee, C. P., Lehtipalo, K., Leiminger, M., Li, Z., Makhmutov, V., Manninen, H. E., Marie, G., Marten, R., Mathot, S., Mauldin, R. L., Mentler, B., Möhler, O., Müller, T., Nie, W., Onnela, A., Petäjä, T., Pfeifer, J., Philippov, M., Ranjithkumar, A., Saiz-Lopez, A., Salma, I., Scholz, W., Schuchmann, S., Schulze, B., Steiner, G., Stozhkov, Y., Tauber, C., Tomé, A., Thakur, R. C., Väisänen, O., Vazquez-Pufleau, M., Wagner, A. C., Wang, Y., Weber, S. K., Winkler, P. M., Wu, Y., Xiao, M., Yan, C., Ye, Q., Ylisirniö, A., Zauner-Wieczorek, M., Zha, Q., Zhou, P., Flagan, R. C., Curtius, J., Baltensperger, U., Kulmala, M., Kerminen, V.-M., Kurtén, T., et al.: Role of iodine oxoacids in atmospheric aerosol nucleation, *Science*, 371, 589–595, <https://doi.org/10.1126/science.abe0298>, 2021.

Huang, J. and Jaeglé, L.: Wintertime enhancements of sea salt aerosol in polar regions consistent with a sea ice source from blowing snow, *Atmospheric Chemistry and Physics*, 17, 3699–3712, <https://doi.org/10.5194/acp-17-3699-2017>, 2017.

Huang, J., Jaeglé, L., Chen, Q., Alexander, B., Sherwen, T., Evans, M. J., Theys, N., and Choi, S.: Evaluating the impact of blowing-snow sea salt aerosol on springtime BrO and O₃ in the Arctic, *Atmospheric Chemistry and Physics*, 20, 7335–7358, <https://doi.org/10.5194/acp-20-7335-2020>, 2020.

Jokinen, T., Sipilä, M., Kontkanen, J., Vakkari, V., Tisler, P., Duplissy, E.-M., Junninen, H., Kangasluoma, J., Manninen, H. E., Petäjä, T., Kulmala, M., Worsnop, D. R., Kirkby, J., Virkkula, A., and Kerminen, V.-M.: Ion-induced sulfuric acid–ammonia nucleation drives particle formation in coastal Antarctica, *Science Advances*, 4, eaat9744, <https://doi.org/10.1126/sciadv.aat9744>, 2018.

Jones, A. E., Anderson, P. S., Begoin, M., Brough, N., Hutterli, M. A., Marshall, G. J., Richter, A., Roscoe, H. K., and Wolff, E. W.: BrO, blizzards, and drivers of polar tropospheric ozone depletion events, *Atmospheric Chemistry and Physics*, 9, 4639–4652, <https://doi.org/10.5194/acp-9-4639-2009>, 2009.

Junninen, H., Ehn, M., Petäjä, T., Luosujärvi, L., Kotiaho, T., Kostianen, R., Rohner, U., Gonin, M., Fuhrer, K., Kulmala, M., and Worsnop, D. R.: A high-resolution mass spectrometer to measure atmospheric ion composition, *Atmospheric Measurement Techniques*, 3, 1039–1053, <https://doi.org/10.5194/amt-3-1039-2010>, 2010.

Karlsson, L., Krejci, R., Koike, M., Ebell, K., and Zieger, P.: A long-term study of cloud residuals from low-level Arctic clouds, *Atmospheric Chemistry and Physics*, 21, 8933–8959, <https://doi.org/10.5194/acp-21-8933-2021>, 2021.



Kirkby, J., Curtius, J., Almeida, J., Dunne, E., Duplissy, J., Ehrhart, S., Franchin, A., Gagné, S., Ickes, L., Kürten, A., Kupc, A., Metzger, A., Riccobono, F., Rondo, L., Schobesberger, S., Tsagkogeorgas, G., Wimmer, D., Amorim, A., Bianchi, F., Breitenlechner, M., David, A., Dommen, J., Downard, A., Ehn, M., Flagan, R. C., Haider, S., Hansel, A., Hauser, D., Jud, W., Junninen, H., Kreissl, F., Kvashin, A., Laaksonen, A., Lehtipalo, K., Lima, J., Lovejoy, E. R., Makhmutov, V., Mathot, S., Mikkilä, J., Minginette, P., Mogo, S., Nieminen, T., Onnela, A., Pereira, P., Petäjä, T., Schnitzhofer, R., Seinfeld, J. H., Sipilä, M., Stozhkov, Y., Stratmann, F., Tomé, A., Vanhanen, J., Viisanen, Y., Vrtala, A., Wagner, P. E., Walther, H., Weingartner, E., Wex, H., Winkler, P. M., Carslaw, K. S., Worsnop, D. R., Baltensperger, U., and Kulmala, M.: Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation, *Nature*, 476, 429–433, <https://doi.org/10.1038/nature10343>, 2011.

Kolarž, P., Gaisberger, M., Madl, P., Hofmann, W., Ritter, M., and Hartl, A.: Characterization of ions at Alpine waterfalls, *Atmospheric Chemistry and Physics*, 12, 3687–3697, <https://doi.org/10.5194/acp-12-3687-2012>, 2012.

Latham, J. and Mason, B. J.: Electric charge transfer associated with temperature gradients in ice, *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 260, 523–536, <https://doi.org/10.1098/rspa.1961.0051>, 1961.

Manninen, H. E., Petäjä, T., Asmi, E., Riipinen, I., Mikkilä, J., Hörrak, U., Mirme, A., Mirme, S., Laakso, L., Kerminen, V.-M., and Kulmala, M.: Long-term field measurements of charged and neutral clusters using Neutral cluster and Air Ion Spectrometer (NAIS), *Bor. Env. Res.*, 14, 591–605, 2009.

Manninen, H. E., Nieminen, T., Asmi, E., Gagné, S., Häkkinen, S., Lehtipalo, K., Aalto, P., Vana, M., Mirme, A., Mirme, S., Hörrak, U., Plass-Dülmer, C., Stange, G., Kiss, G., Hoffer, A., Törő, N., Moerman, M., Henzing, B., de Leeuw, G., Brinkenberg, M., Kouvarakis, G. N., Bougiatioti, A., Mihalopoulos, N., O'Dowd, C., Ceburnis, D., Arneth, A., Svenningsson, B., Swietlicki, E., Tarozzi, L., Decesari, S., Facchini, M. C., Birmili, W., Sonntag, A., Wiedensohler, A., Boulon, J., Sellegri, K., Laj, P., Gysel, M., Bukowiecki, N., Weingartner, E., Wehrle, G., Laaksonen, A., Hamed, A., Joutsensaari, J., Petäjä, T., Kerminen, V.-M., and Kulmala, M.: EUCAARI ion spectrometer measurements at 12 European sites – analysis of new particle formation events, *Atmos. Chem. Phys.*, 10, 7907–7927, <https://doi.org/10.5194/acp-10-7907-2010>, 2010.

Mirme, A., Tamm, E., Mordas, G., Vana, M., Uin, J., Mirme, S., Bernotas, T., Laakso, L., Hirsikko, A., and Kulmala, M.: A wide-range multi-channel Air Ion Spectrometer, *Boreal Environment Research*, 12, 247–264, 2007.

Mirme, S. and Mirme, A.: The mathematical principles and design of the NAIS – a spectrometer for the measurement of cluster ion and nanometer aerosol size distributions, *Atmospheric Measurement Techniques*, 6, 1061–1071, <https://doi.org/10.5194/amt-6-1061-2013>, 2013.

Nishimura, K. and Nemoto, M.: Blowing snow at Mizuho station, Antarctica, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 363, 1647–1662, <https://doi.org/10.1098/rsta.2005.1599>, 2005.

Quéléver, L. L. J., Dada, L., Asmi, E., Lampilahti, J., Chan, T., Ferrara, J. E., Copes, G. E., Pérez-Fogwill, G., Barreira, L., Aurela, M., Worsnop, D. R., Jokinen, T., and Sipilä, M.: Investigation of new particle formation mechanisms and aerosol



- processes at Marambio Station, Antarctic Peninsula, *Atmospheric Chemistry and Physics*, 22, 8417–8437, <https://doi.org/10.5194/acp-22-8417-2022>, 2022.
- Reynolds, S. E., Brook, M., and Gourley, M. F.: Thunderstorm charge separation, *Journal of the Atmospheric Sciences*, 14, 426–436, [https://doi.org/10.1175/1520-0469\(1957\)014<0426:TCS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1957)014<0426:TCS>2.0.CO;2), 1957.
- Saunders, C.: Charge Separation Mechanisms in Clouds, in: *Planetary Atmospheric Electricity*, edited by: Leblanc, F., Aplin, K. L., Yair, Y., Harrison, R. G., Lebreton, J. P., and Blanc, M., Springer, New York, NY, 335–353, https://doi.org/10.1007/978-0-387-87664-1_22, 2008.
- Savelyev, S. A., Gordon, M., Hanesiak, J., Papakyriakou, T., and Taylor, P. A.: Blowing snow studies in the Canadian Arctic Shelf Exchange Study, 2003–04, *Hydrological Processes*, 20, 817–827, <https://doi.org/10.1002/hyp.6118>, 2006.
- Schmidt, D. S., Schmidt, R. A., and Dent, J. D.: Electrostatic Force in Blowing Snow, *Boundary-Layer Meteorology*, 93, 29–45, <https://doi.org/10.1023/A:1002045818907>, 1999.
- Simpson, G. C.: *Meteorology - Atmospheric electricity*, British Antarctic Expedition 1910-1913, Vol. 1, 1921.
- Sipilä, M., Sarnela, N., Jokinen, T., Henschel, H., Junninen, H., Kontkanen, J., Richters, S., Kangasluoma, J., Franchin, A., Peräkylä, O., Rissanen, M. P., Ehn, M., Vehkamäki, H., Kurten, T., Berndt, T., Petäjä, T., Worsnop, D., Ceburnis, D., Kerminen, V.-M., Kulmala, M., and O’Dowd, C.: Molecular-scale evidence of aerosol particle formation via sequential addition of HIO₃, *Nature*, 537, 532–534, <https://doi.org/10.1038/nature19314>, 2016.
- Smith, D. and Spänel, P.: Ions in the terrestrial atmosphere and in interstellar clouds, *Mass Spectrometry Reviews*, 14, 255–278, <https://doi.org/10.1002/mas.1280140403>, 1995.
- Takahashi, T.: Riming Electrification as a Charge Generation Mechanism in Thunderstorms, *Journal of the Atmospheric Sciences*, 35, 1536–1548, [https://doi.org/10.1175/1520-0469\(1978\)035<1536:REAACG>2.0.CO;2](https://doi.org/10.1175/1520-0469(1978)035<1536:REAACG>2.0.CO;2), 1978.
- Tammet, H., Horrak, U., and Kulmala, M.: Negatively charged nanoparticles produced by splashing of water, *Atmos. Chem. Phys.*, 2009.
- Tigges, L., Jain, A., and Schmid, H.-J.: On the bipolar charge distribution used for mobility particle sizing: Theoretical considerations, *Journal of Aerosol Science*, 88, 119–134, <https://doi.org/10.1016/j.jaerosci.2015.05.010>, 2015.
- Tkachenko, K. and Jacobi, H.-W.: Electrical charging of snow and ice in polar regions and the potential impact on atmospheric chemistry, *Environmental Science: Atmospheres*, 4, 144–163, <https://doi.org/10.1039/D3EA00084B>, 2024.
- Virkkula, A., Hirsikko, A., Vana, M., Aalto, P. P., Hillamo, R., and Kulmala, M.: Charged particle size distributions and analysis of particle formation events at the Finnish Antarctic research station Aboa, *BER*, 12, 397–408, 2007.
- Wagenbach, D., Ducroz, F., Mulvaney, R., Keck, L., Minikin, A., Legrand, M., Hall, J. S., and Wolff, E. W.: Sea-salt aerosol in coastal Antarctic regions, *Journal of Geophysical Research: Atmospheres*, 103, 10961–10974, <https://doi.org/10.1029/97JD01804>, 1998.
- Wagner R., Manninen H.E., Franchin A., Lehtipalo K., Mirme S., Steiner G., Petäjä T. and Kulmala M., On the accuracy of ion measurements using a Neutral cluster and Air Ion Spectrometer, *Boreal Environment Research*, 21, (2016), pp. 230–241.



- Wang, S. C. and Flagan, R. C.: Scanning Electrical Mobility Spectrometer, *Aerosol Science and Technology*, 13, 230–240, <https://doi.org/10.1080/02786829008959441>, 1990.
- Wiedensohler, A., Lütkeemeier, E., Feldpausch, M., and Helsper, C.: Investigation of the bipolar charge distribution at various gas conditions, *Journal of Aerosol Science*, 17, 413–416, [https://doi.org/10.1016/0021-8502\(86\)90118-7](https://doi.org/10.1016/0021-8502(86)90118-7), 1986.
- Wiedensohler, A., Birmili, W., Nowak, A., Sonntag, A., Weinhold, K., Merkel, M., Wehner, B., Tuch, T., Pfeifer, S., Fiebig, M., Fjåraa, A. M., Asmi, E., Sellegri, K., Depuy, R., Venzac, H., Villani, P., Laj, P., Aalto, P., Ogren, J. A., Swietlicki, E., Williams, P., Roldin, P., Quincey, P., Hüglin, C., Fierz-Schmidhauser, R., Gysel, M., Weingartner, E., Riccobono, F., Santos, S., Gröning, C., Faloon, K., Beddows, D., Harrison, R., Monahan, C., Jennings, S. G., O’Dowd, C. D., Marinoni, A., Horn, H.-G., Keck, L., Jiang, J., Scheckman, J., McMurry, P. H., Deng, Z., Zhao, C. S., Moerman, M., Henzing, B., de Leeuw, G., Löschau, G., and Bastian, S.: Mobility particle size spectrometers: harmonization of technical standards and data structure to facilitate high quality long-term observations of atmospheric particle number size distributions, *Atmospheric Measurement Techniques*, 5, 657–685, <https://doi.org/10.5194/amt-5-657-2012>, 2012.
- Yang, X., Pyle, J. A., and Cox, R. A.: Sea salt aerosol production and bromine release: Role of snow on sea ice, *Geophysical Research Letters*, 35, <https://doi.org/10.1029/2008GL034536>, 2008.
- Yang, X., Frey, M. M., Rhodes, R. H., Norris, S. J., Brooks, I. M., Anderson, P. S., Nishimura, K., Jones, A. E., and Wolff, E. W.: Sea salt aerosol production via sublimating wind-blown saline snow particles over sea ice: parameterizations and relevant microphysical mechanisms, *Atmospheric Chemistry and Physics*, 19, 8407–8424, <https://doi.org/10.5194/acp-19-8407-2019>, 2019.