The Observation of the Lightning Induced Variations in Atmospheric Ions

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ABSTRACT: Variations in atmospheric ion concentration were studied in a boreal forest in Finland, with emphasis on the effect of lightning. In general, changes in ion concentrations have diurnal and seasonal patterns. Distinct features were found in ions of different size ranges, namely small ions (0.8 – 1.7 nm) and intermediate ions (1.7 – 7 nm). Preliminary results on two case studies of lightning effect are present, one with rain effect and the other not. Bursts in the concentrations of small ions and intermediate ions were observed in both cases. However, different trends in trace gases were observed for the two cases. Further investigation is needed to reveal the nature of lightning ions and the mechanism in their formation. The work is under progress.

INTRODUCTION

Atmospheric ions, or air ions, refer to electric charge carriers present in the atmosphere. Distinct features exist in their chemical composition, mass, size as well as number of carried charges. According to *Tammet* [1998], atmospheric ions can be classified into small or cluster ions, intermediate ions, and large ions based on their mobility (Z) in air, being $Z > 0.5\ \mathrm{cm^2V^{-1}s^{-1}}$, $0.5\ \mathrm{cm^2V^{-1}s^{-1}} \leq Z \geq 0.03\ \mathrm{cm^2V^{-1}s^{-1}}$ and $Z < 0.03\ \mathrm{cm^2V^{-1}s^{-1}}$, respectively. Mobility diameter ranges of ca. 0.8 – 1.7 nm, 1.7 –7 nm and >7 nm in ion spectrometers are often used to refer small, intermediate and large ions.

Small ions dominate the total ion concentration and typically only a few ions exist in the intermediate and large sizes. Increase in intermediate ion concentration is often observed when there is a new particle formation (NPF) event or other processes resulting in the growth of ions in size, such as the cluster event during evening [*Lehtipalo et al.*, 2011] and rain effect [*Hõrrak et al.*, 2006].

Initially, atmospheric ions are formed via the ionization process of air molecules (mainly N_2 and O_2) by environmental radioactivity. The decay emissions of radon and cosmic rays, as well as the terrestrial gamma radiation are the suppliers of the ionizing energy involved in this process [*Hirsikko et al.*, 2011], under fair-weather conditions [*Harrison and Carslaw*, 2003]. The resulted ions are known as primary ions. Via going through a series of subsequent collisions with other trace gases, small air ions can be produced. The further ion-ion recombination and ion-neutral attachment will lead to ion-mediated nucleation (IMN), which can potentially contribute to the burst in particle concentration, known as NPF. Nucleation without the involvement of ion-ion recombination is usually term as ion-induced nucleation (IIN) [*Manninen et al.*,

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2010; *Yu and Turco*, 2008]. Apart from the aforementioned components in atmospheric radioactivity, high-strength electric field can assist the production of atmospheric ions [*Israël*, 1970]. A good candidate in nature for such an occasion is a lightning event.

The high-energy electric field induced during a lightning strike can endue an electron with sufficient kinetic energy and transmute it into runaway electron [*Dwyer et al.*, 2012]. When this energetic runaway electron moves in atmosphere, it can produce avalanche multiplication. Likewise, a positive proton can also be accelerated and trigger the avalanche process [*Greenfield et al.*, 2003]. This mechanism has been hypothesised as the reason of the terrestrial gamma flashes (TGFs) observed during lightning episodes [*Dwyer et al.*, 2012]. The generated charges are potentially the source of atmospheric ions.

In this abstract, long-term trends in atmospheric ions and preliminary results of case studies on lightning and rain effects are shown, together with the gamma radiation and trace gases for the speculation of the possible reasons for the observations. Results are presented in Finnish winter time (UTC+2).

MEASUREMENTS AND MEHODS

The measurement site, Hyytiälä SMEAR II station (61°50'40" N, 24°17'13"E), providing data used in this study, locates in a boreal forest in Southern Finland [*Kulmala et al.*, 2001]. It is a well-equipped station for the study of the relationship between atmosphere and biosphere and a super site serving research activities in atmospheric sciences, especially on aerosol study. The continuous measurement of aerosol particles at SMEAR II can be dated back to the year of 1996 with a Differential Mobility Particle Sizer (DMPS) [*Kulmala et al.*, 2012; *Wiedensohler et al.*, 2012]. Meteorological parameters and trace gases have been measured since 1996. For ions, the measurement started in 2003.

This abstract will present results based on the ion data collected from a Neutral cluster and Air Ion Spectrometer (NAIS) [*Manninen et al.*, 2009] and a Balanced Scanning Mobility Analyzer (BSMA) [*Tammet*, 2006]. Both instruments are ion spectrometers and generating number size distribution data on atmospheric ions. The inlets are at around two meters above ground. The NAIS has a measurable mobility size range of 0.8 – 42 nm and the BSMA of 0.8 – 8 nm. In addition to atmospheric ions, the NAIS can also provide information on neutral aerosol particles in the mobility size range of 2.5 – 20 nm. This site is also equipped with a radon monitor and a pressurized ionization chamber for the measurement of ionizing gamma radiation. The meteorological and trace gas data are collected from the long-term mast measurement at SMAER II station. The mast has a height of 127 m and measurements are carried out at 10 height-levels. The lightning data is acquired from the Nordic lightning location system (NORDLIS), which consists of about 30 ground-based sensors in Finland, Sweden, Norway, and Estonia [*Mäkelä et al.*, 2010].

RESULTS AND DISCUSSION

FAIR WEATHER

Under fair weather conditions, atmospheric ions have distinct diurnal and seasonal patterns for different size ranges. In general, slightly more positive small ions can be observed at ground level due to the earth electrode effect. For year 2009 – 2012, the annual median concentration was 663±46 cm^{-3} for small positive ions based on the BSMA measurement and 639±77 cm^{-3} for the negative polarity

(380±27 cm^{-3} for small positive ions and 352±22 cm^{-3} for small negative ion based on the NAIS). The earth ground is slightly negatively charged resulting in a weak repelling force on the negative ions near the earth surface [*Hirsikko et al.*, 2011], which the other hand, has affinity to the positive ions.

Owing to the different instrumental design in the NAIS and BSMA, divergence exists in the concentrations of small ions observed by them: the BSMA typically gives twice the amount of atmospheric ions shown in the NAIS. The highest small ion concentration was found in summer. Also clear diurnal profile was observed in this season with low concentration at noon and high in the evening. Similar variation was seen in spring time as well. These phenomena could be attributed to the frequent occurrence of NPF event around noon and the development of boundary layer. The evidence was observed in intermediate ions, too.

For intermediate ions, both instruments give similar results in concentration. High concentrations were found in summer and spring. The highest amount of ions was observed in spring for the negative polarity (46±24 cm^{-3} in the BSMA), which could be owing to the fact that NPF event happens more often in negative ions than in positive ones. As for the diurnal cycles, on the contrary to small ions, concentration peaked around noon in the intermediate size range in spring and summer. However, similarly, high concentration was seen in the evening as well, which is related to the shrinking of boundary layers.

THUNDERSTORMS

On average, the region where SMAER II station locates can encounter about 12 thunderstorms between May and August every year. Quite often, lightning occurs simultaneously with or slightly ahead the recorded rain at ground level. Increase in ion concentration, especially in the negative polarity, has been observed during rain episodes [*Hirsikko et al.*, 2007; *Hõrrak et al.*, 2006]. Tammet et al. [2009] has studied the phenomenon in laboratory with rain simulation by splashing water. He stated that the concentration burst during rain is related to the baloelectric effect and found intermediate ions with similar mobility in the simulation experiment to those observed during rain. However, the mechanism lying behind the charge production is still not clear. In addition, these baloelectric ions are suggested to be singly charged and tend to shrink with time and thus differ from the ones formed during NPF event [*Tammet et al.*, 2009].

A case study of thunderstorm effect was present in Figure 1. Precipitation was sensed at 10:46, shortly after the first record of lightning at 10:45 on this day. The shoot in the concentration of negative intermediate ions was observed at about the same time, which can be related to the baloelectric effect explained by *Tammet et al.* [2009] and to the observations by *Hõrrak et al.* [2006] and *Hirsikko et al.* [2007]. According to Hõrrak et al., small ion concentration tend to decrease during rain in the positive polarity [*Hõrrak et al.*, 2006]. However, a burst in the amount of small ions occurred on July 7, 2010, when intensive lightning strikes were detected. It seems that this increase in small ion concentration can be speculated as a result of the lightning effect. Apart from variations in ion concentration, also fluctuations in trace gases were found. O_3 concentration declined after the first lightning strike recorded (Figure 2). Correspondingly, an increase in water concentration appeared at the same time.

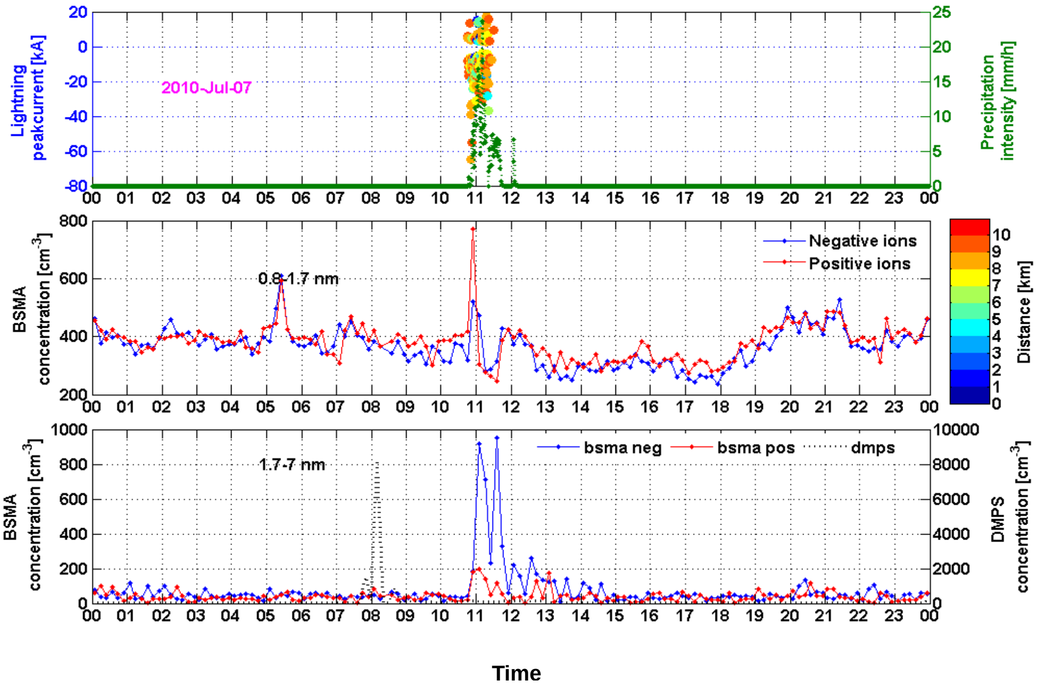

Figure 1: lightning, rain and ion concentrations on July 7, 2010. The dots in the upper panel represent the detected lightning strikes and precipitation is shown in green dotted line. The color of the lightning dots indicates the distance of lightning strikes from the SMEAR II station. Small ion concentration measured with the BSMA shown in the middle panel and the intermediate ion concentration in the lower panel. Total particle concentration between 3-7 nm obtained from the DMPS is given on the right-hand-side axis in the lower panel.

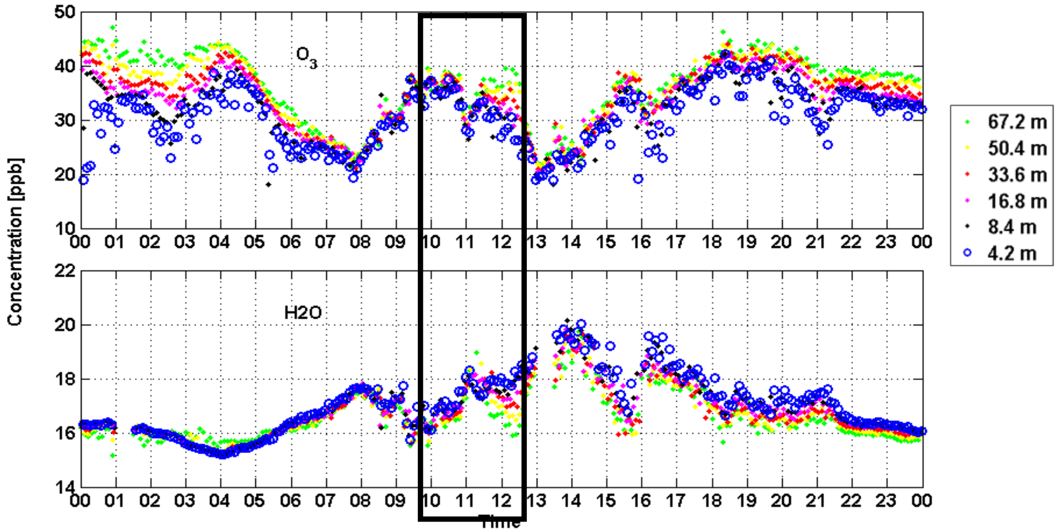

Figure 2: variations in O_3 and H_2O concentration associated with thunderstorm on July 7, 2010. Colors indicate the height of the measurements. The frame outlines the changes in O_3 and H_2O concentration associated with lightning.

Out of 98 days with observed lightning events, precipitation was absent on only 8 days during the lightning episodes. And for most of these days, the lightning flashes had relatively low peak current. Lightning was also observed sometimes after a low-intensity rain. The results of such a day are illustrated in Figure 3. The rain, with maximum intensity less than 0.4 mm/h, stopped at 18:42, but lightning lasted till around 19:05. Increases in both small and intermediate ions were observed right after the lightning. However, a slight decrease was seen in the total particle concentration by the DMPS. No influence of washed-out radon progeny was found based on the ionization chamber measurement (Figure 4). However, owing to the low time resolution (10 min) of this device, no evidence on the TGFs can be obtained to explain the mechanism in the formation of these lightning ions.

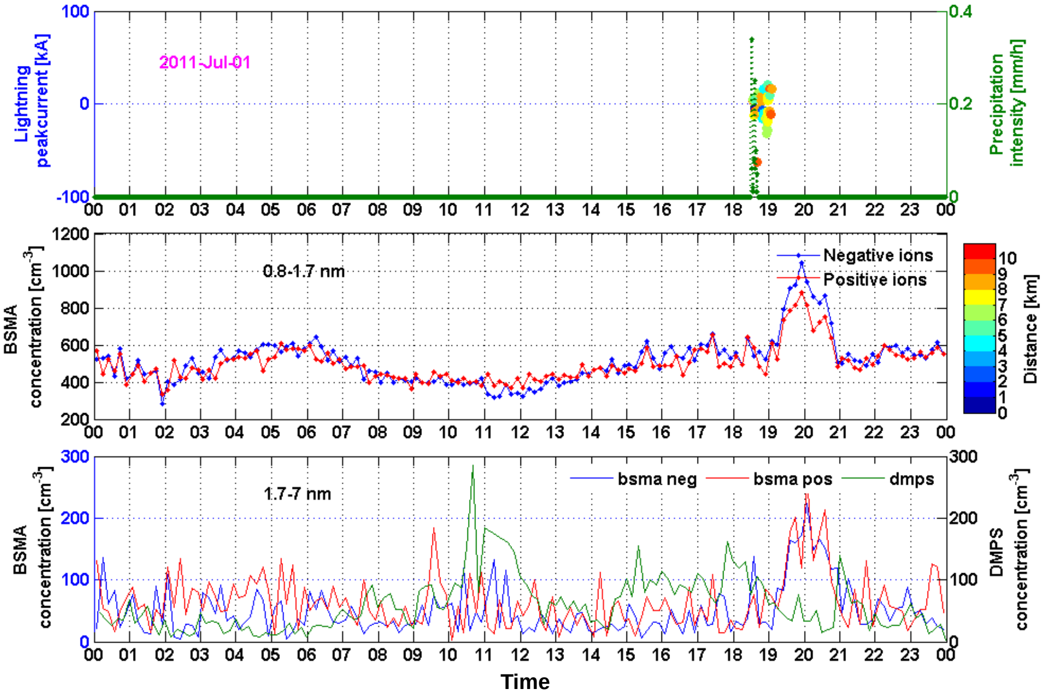

Figure 3: lightning, rain and ion concentrations on July 1, 2011. The dots in the upper panel represent the detected lightning strikes and precipitation is shown in green dotted line. The color of the lightning dots indicates the distance of lightning strikes from the SMEAR II station. Small ion concentration measured with the BSMA shown in the middle panel and the intermediate ion concentration in the lower panel. Total particle concentration between 3-7 nm obtained from the DMPS is given on the right-hand-side axis in the lower panel.

Alterations in O_3 and H_2O concentrations were also spotted in relation to lightning strikes. However, in contrast to the phenomena on July 7, 2010, O_3 concentration was raised, along with a reduction in H_2O concentration (Figure 5). This suggests that the increase in ion concentration was not a night-time cluster event, for during which a decrease in O_3 and an increase in H_2O were usually seen, as the one happened around 21:00 on July 7, 2010 (Figure 2).

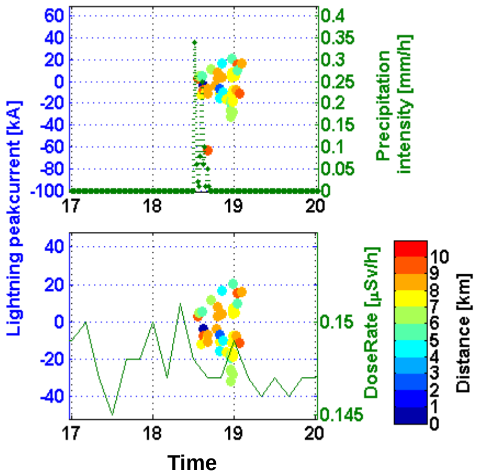

Figure 4: lightning, rain and gamma radiation dose rate on July 1, 2011.

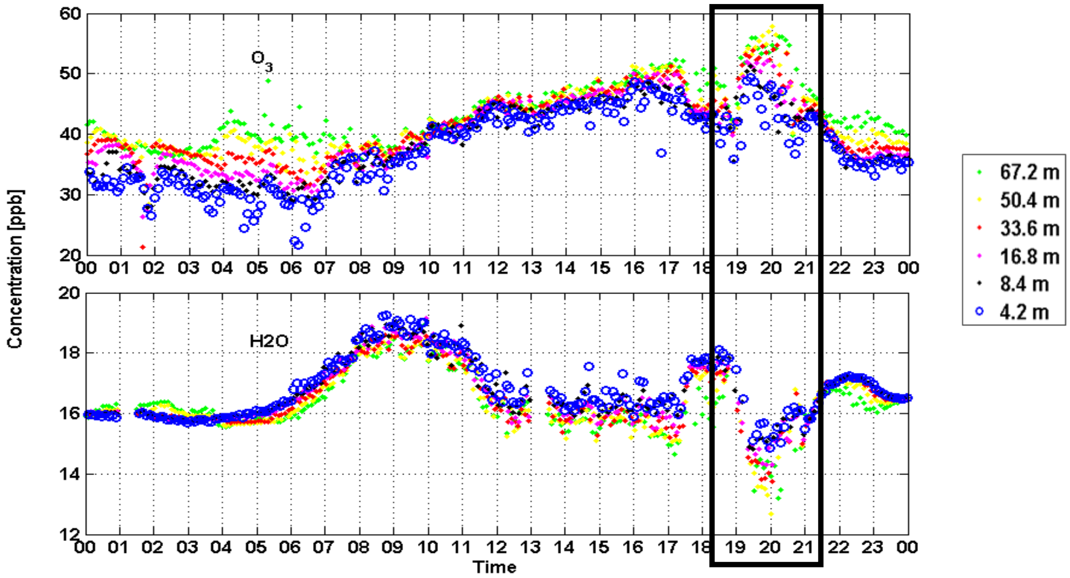

Figure 5: variations in O_3 and H_2O concentration associated with lightning on July 1, 2011. Colors indicate the height of the measurements. The frame outlines the changes in O_3 and H_2O concentration associated with lightning.

CONCLUSIONS

Diurnal cycles exist in ion concentrations of different size ranges, especially in spring and summer. The low concentration in small ions around noon is related to the development of boundary layer and NPF event. The nucleation and growth during NPF event result in the observed high concentration around noon in the intermediate size range of ions. Bursts in the concentration of intermediate ions were also found during lightning and rain episodes. Tammet et al., however, pointed out rain ions are baloelectric ions, which differ from the intermediate ions involved in NPF by their evaporating characteristics [2009]. Two case studies were presented for variations in ions related to lightning events. Opposite trends in O_3 and H_2O concentrations were observed in association with lightning effect in these cases. Rain could be the reason for the divergence in the observations. Nevertheless, the nature of these lightning ions and the mechanism behind their formation requires further investigation and the work is under progress.

ACKNOWLEDGMENTS

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REFERENCES

Dwyer, J. R., D. M. Smith, and S. A. Cummer (2012), High-Energy Atmospheric Physics: Terrestrial Gamma-Ray Flashes and Related Phenomena, *Space Science Reviews*, *173*(1-4), 133-196, doi:10.1007/s11214-012-9894-0.

Greenfield, M. B., A. T. Domondon, S. Tsuchiya, K. Kubo, Y. Ikeda, and M. Tomiyama (2003), Near-ground detection of atmospheric γ rays associated with lightning, *Journal of Applied Physics*, *93*(3), 1839, doi:10.1063/1.1536731.

Harrison, R. G., and K. S. Carslaw (2003), Ion-aerosol-cloud processes in the lower atmosphere, *Reviews of Geophysics*, *41*(3), 1012, doi:10.1029/2002RG000114.

Hirsikko, A., T. Bergman, L. Laakso, M. D. Maso, I. Riipinen, U. Hõrrak, and M. Kulmala (2007), Identification and classification of the formation of intermediate ions measured in boreal forest, *Atmos. Chem. Phys.*, *7*, 201–210.

Hirsikko, A., et al. (2011), Atmospheric ions and nucleation: a review of observations, *Atmospheric Chemistry and Physics*, *11*(2), 767-798, doi:10.5194/acp-11-767-2011.

Hõrrak, U., H. Tammet, P. P. Aalto, M. Vana, A. Hirsikko, L. Laakso, and M. Kulmala (2006), Formation of Charged Nanometer Aerosol Particles Associated with Rainfall: Atmospheric Measurements and Lab Experiment, *Report Series in Aerosol Science*, *80*, 180-185.

Israël, H. (1970), *Atmospheric electricity, Vol. I*, Israel Program for Scientific Translations, Jerusalem.

Kulmala, M., et al. (2001), Overview of the international project on biogenic aerosol formation in the boreal forest (BIOFOR), *Tellus*, *53B*, 324-343.

Kulmala, M., et al. (2012), Measurement of the nucleation of atmospheric aerosol particles, *Nature protocols*, *7*(9), 1651-1667, doi:10.1038/nprot.2012.091.

Lehtipalo, K., M. Sipilä, H. Junninen, M. Ehn, T. Berndt, M. K. Kajos, D. R. Worsnop, T. Petäjä, and M. Kulmala (2011), Observations of Nano-CN in the Nocturnal Boreal Forest, *Aerosol Science and Technology*, *45*(4), 499-509, doi:10.1080/02786826.2010.547537.

Manninen, H. E., et al. (2010), EUCAARI ion spectrometer measurements at 12 European sites – analysis of new particle formation events, *Atmospheric Chemistry and Physics*, *10*(16), 7907-7927, doi:10.5194/acp-10-7907-2010.

Manninen, H. E., et al. (2009), Long-time field measurements of charged and neutral clusters using Neutral cluster and Air Ion Spectrometer (NAIS) *Boreal Environment Reseach*, *14*, 591-605.

Mäkelä, A., T. J. Tuomi, and J. Haapalainen (2010), A decade of high-latitude lightning location: Effects of the evolving location network in Finland, *Journal of Geophysical Research*, *115*(D21), doi:10.1029/2009jd012183.

Tammet, H. (1998), Air ions, in *CRC Handbook of Chemistry and Physics*, edited, pp. 32-34 CRC Press, Boca Raton, Ann Arbor, London, Tokyo

Tammet, H. (2006), Continuous scanning of the mobility and size distribution of charged clusters and nanometer particles in atmospheric air and the Balanced Scanning Mobility Analyzer BSMA, *Atmospheric Research*, *82*(3-4), 523-535, doi:10.1016/j.atmosres.2006.02.009.

Tammet, H., U. Hõrrak, and M. Kulmala (2009), Negatively charged nanoparticles produced by splashing of water, *Atmos. Chem. Phys.*, *9*, 357–367.

Wiedensohler, A., et al. (2012), 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*(3), 657-685, doi:10.5194/amt-5-657-2012.

Yu, F., and R. Turco (2008), Case studies of particle formation events observed in boreal forests: implications for nucleation mechanisms, *Atmos. Chem. Phys.*, *8*, 6085–6102.