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CHARACTERIZATION OF THE ATMOSPHERIC ELECTRICAL ENVIRONMENT NEAR A CORONA ION EMITTING SOURCE.

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Abstract

Presence of high concentrations of corona ions in any air environment cause changes in the earth's natural dc e-field; while their interaction with airborne aerosols produce charged particles. The charged particles and ions are dispersed by wind, and depending on the prevailing meteorology, their presence can be observed several hundreds of meters from the ion source. This paper presents a study characterizing the electrical environment of a strong substantially-constant source of corona ions (a high voltage electricity substation).

Results of the study showed that corona ion and particle charge concentrations as well as their associated effect on the vertical dc e-field perturbations decreased with distance from the emitting source. Mean particle charge concentration in the air environment of the ion emitting source (-1750 ± 745 ions cm^{-3}) was three times higher than that of an urban outdoor air and seventeen times that of a mechanically ventilated room. Statistical investigation of possible associations between parameters showed strong associations (R^2 = 74%, P<0.05) between particle charge and ion concentration; and 54% correlation between particle charge and magnitude of the vertical dc e-field (mean value of -285 ± 51 V m^{-1}). Although a source of ambient electrical charge, the electricity substation was not a significant generator of aerosol particles within the size range (0.02 to 1 μm) examined in this study.

Keywords: Ambient aerosol, charged particle, corona discharge, high voltage, transmission substation.

1.0 Introduction

One of the sources of corona ions in our industrial society are high voltage electrical installations like powerlines and substations (Carter and Johnson 1988; Johnson 1990; Abdel-Salam and Abdallah 1993). Corona ion emission occurs when the electric field gradient at the surface of high voltage current carrying conductors exceeds a certain critical voltage value known as the onset voltage for corona discharge. This onset voltage is dependent on factors such as the voltage of the conductor to ground, conductor surface conditions (particle deposition level, presence of protrusions, etc.), number of sub-conductors per phase used for the transmission, conductor characteristics of age, diameter, etc. and the prevailing meteorological conditions (Suda et al. 1988; CIGRE 1993; Phillips et al. 1999; Maruvada 2000; Nie et al. 2001; MacAlpine and Zhang 2003).

Apart from line conductors, other components of electrical installations including connectors, metal fittings between disc insulators, separators and line spacers, are also susceptible to corona discharge. Release of net unipolar ions, into the atmosphere by these infrastructures is often associated with variation in the earth's natural direct current (dc) electric field (e-field) of around $100Vm^{-1}$, and this effect is measurable at the ground level (CIGRE 1993; Wilding et al. 2000; Abdel-Salam and Abdel-Aziz 2001; Fews et al. 2002; Bracken et al. 2005). Once in the atmosphere, the ions are carried in the wind and depending on the prevailing wind velocity, their presence can be observed at some distance away from the source (Wilding et al. 2000). Various studies have been conducted on corona emission by high voltage powerlines (HVPLs) and their effect on the earth's dc e-field (Carter and Johnson 1988; Abdel-Salam et al. 1990; Wilding et al. 2000; Fews et al. 2002); their impact on atmospheric chemistry (Delory et al. 2006; Farrell et al. 2006) and on biological systems (Guler and Seyhan 2001). However, no attempt has yet been made to simultaneously quantify or investigate associations between parameters characterizing electrical environments (i.e. ion concentration, particle charge concentration, e-field, etc.) near corona ion emitting sources such as HVPLs, and electricity substations.

Electrical infrastructures (HVPLs, electricity substations, etc.) are essential to the power transmission and distribution process, as they play vital roles of receiving high voltage electricity from generating stations and delivering at a reduced voltage to the end users. Major power transmission and distribution systems are preferably located away from residential / public housing and most human activities, but with increased demand for land development, cities will expand and more of these infrastructures are likely to be located in the future, closer to residential/public buildings and other human activities. Consequently, a study of this nature has the potential to provide more understanding on the localized effects of corona ions, while also assessing its other potential impacts.

The aims of this study were therefore to characterize the electrical environment around a high voltage device, identified as producing a strong substantially-constant source of corona ions; investigate the association between parameters characterising such an environment; and assess the effect of wind on the instantaneous value of the parameters measured. To achieve these aims, the use of a strong localized, highly concentrated source of corona ions and charged aerosol particles was required. In the proximity of this source, direct measurements were made of airborne particle charge concentration, net space charge concentration and vertical dc electric field. Although the corona ion source used in this study was an electricity transmission substation; the focus of this paper was not to conduct a full characterization of the nature and type of emission generated by the substation but rather to employ the substation as a strong localised, near-ground source of corona ions (unlike overhead power conductors which are suspended well above ground with steel, concrete or wooden structures). Relationships between parameters and the effect of wind were investigated using statistical regression analysis.

2.0 Methods

In carrying out this study, five different electricity substations were assessed but only one provided enough access and distance of more than 5 m from the substation fence. This paper presents the results of a 5 hour study conducted near one of the substations, during which period the meteorological conditions were suitable for the measurements conducted. Being a pilot study and a basis for all other more comprehensive and detailed investigations, the conditions during sampling was specifically chosen to reduce complexities that may arise with the large number of potential variables known to affect a study of this nature. Consequently, it was paramount to conduct measurements under a very fine weather of clear sky, in the absence of rain or any other form of precipitation that may reduce airborne particle concentration (washouts); no electrified rain clouds (which can also affect the sign and magnitude of the vertical dc e-field); prevailing wind direction must be from the corona ion source to the sampling instruments as the objective of the study was to quantify the effect of the ion source on it environment; wind speed must be slight to moderate in order to avoid turbulence which may bring about re-suspension of already settled particles into the air environment; and it was also necessary to select a time when the relative humidity of the air was less than 70 %, for the reliable operation of the aerosol electrometer.

2.1 Measurement site

The main measurements were conducted in the proximity of an electricity transmission voltage substation (voltage of between 220 kV and 330 kV). The site was particularly suitable because of its flat topography, accessibility and high concentration of space charge (corona ions), which was well above those of an urban outdoor air (i.e. an environment well away from industrial, traffic, or HVPL sites). The prevailing meteorology as of the time of sampling fulfilled the desired condition, with the wind direction being from the substation towards the sampling sites. Control measurements were also conducted in: (i) a mechanically ventilated room, and (ii) a typical urban outdoor air environment.

2.2 Instrumentation

Instruments used in this study for the characterization of environmental particles and ions were: a portable TSI model 8525 P-Trak ultrafine particle counter (P-Trak); a TSI Model 3068 Aerosol Electrometer (AE); an AlphaLab air ion counter (AIC); John Chubb Instrumentation (JCI) 140 Static Monitor e-field meters; and a Monitor Sensors automated weather station with µSmart series sensors and data logger.

The P-Trak is designed for real-time measurement of aerosol particles in the size range of 0.02 to 1 µm (TSI 2004). Equipped with an in-built memory for data storage, this instrument was used to measure the total number concentration of airborne particles around the corona ion emitting source. The AE employed for measuring airborne particle charge concentration was designed to measure net charge on aerosol particles within the size range of 0.002 to 5 µm (TSI 2003). For data logging purposes, this instrument was connected to a computer using an analogue to digital converter (ADC). The suitability, limitations and optimal operating conditions for using AE to measure ambient particle charges was established in the study by J-Fatokun et al. (2007). Space charge concentration in the proximity of the corona ion source was measured with the AIC. Designed for measuring air ion concentration levels, the AIC's output are due to ions collected on its internal plate. The JCI 140 e-field meters used in monitoring vertical dc e- field near the strong corona ion source have resolutions of 10 V m^{-1} and were designed for a field range of -20.000 V to +20.000 V. During sampling, the meters were placed at a fixed height of 1.5 m above ground, their output signals were digitised and transmitted via a wireless system to a computer for data logging. Wind speed and wind direction was measured using an automated weather station.

2.3 Measurement techniques and study design

Immediately before conducting any e-field measurements, the magnitude of the earth's dc e-field was measured in the same locality, but well away from any electrical infrastructure or electrified clouds and found to be 70 V m^{-1}. This value was taken as the earth's natural dc e-field for the sampling site and subsequently subtracted from all e-field readings in this study, to obtain the change in magnitude of the vertical dc e-field due to the ions released by the strong corona ion source. With all sampling instruments set to log data at a time interval of 1 second, the P-Trak, AE, meteorological station and e-field meter (Ef_1) were placed at a fixed point (S_1 = 5 m) from the substation fence. Two additional e-field meters (Ef_2 and Ef_3) were also positioned at distances of 17 m (S_2) and 27 m (S_3) respectively The AIC was used for spot measurements of ion concentration as a function of distance (diagonal and perpendicular) from the substation fence. While ion concentration measurements made in the perpendicular direction (at distances of 6 m, 7 m, 20 m and 33 m) to the fence were designed to align with the positions of the e-field meters, those made in the diagonal direction (at 9 m, 20 m, 28 m and 40 m) were directly downwind of the corona ion source. The orientation of the meteorological station at the sampling site was such that a 90^o wind direction represented winds blowing directly from the source to the sampling site; 0^o represented true north and 270^o represented winds from the sampling site to the corona source. Figure 1 is a schematic diagram of the corona ion site and positions of sampling equipment. (INSERT FIGURE 1).

Ambient ion concentrations in the proximity of any electrical infrastructure are indications of the excess unipolar ions present in such an environment. In understanding how concentrations in the environment of the corona ion source deviate from those of other air environments, net particle charge concentrations around the corona source were compared to those obtained from: (i) an urban outdoor and (ii) a mechanically ventilated room. Linear associations were estimated and tested using Pearson correlations, while differences in mean levels between these three air environments were tested using analysis of variance (ANOVA). Links between parameters characterizing the environment around the corona ion source were investigated by (i) monitoring their time-series pattern, and (ii) using simple linear regression analysis, the strength of these regressions was tested using the coefficient of determination R^2. Statistical significance was asserted at the 5% level.

3.0 Results

3.1 Relationship between particle charge, particle number, ion concentration and dc e-field.

The charge present in the air environment of the transmission voltage substation was predominantly negative. Net aerosol particle charge concentration measured by the AE, ion concentration measured by the AIC and the dc e-field measured by the e-field meters were also all of the negative polarity. Using the AE, mean net particle charge concentrations of -1750 ions cm^{-3} and a maximum of -3693 ions cm^{-3} were found to be present in the air around the corona source - a value three times higher than that measured in the urban outdoor air and over seventeen times that of the mechanically ventilated room (Figure 2a). The measured difference in particle charge concentrations between these three different air environments were statistically significant ($p<0.05$). Figure 2b gives a section of the time series variation of these net particle charge concentrations. (INSERT FIGURES 2a AND 2b).

Corona ions increased the local vertical dc e-field by -286 V m^{-1}, -260 V m^{-1} and -178 V m^{-1} at respective distances of 5 m, 17 m and 27 m from the substation fence. Generally, though there exist some variability, the results showed that ion concentration and e-field perturbations decreased with distance from the corona ion source (Figure 3). The mean aerosol particle number concentration was (3.8 ± 0.4) x 10^3 particle cm^{-3}. (INSERT FIGURE 3).

Results of comparative analysis conducted between instruments used for characterizing the electrical environment near the corona ion source revealed that when sampling with the AE and AIC at the same distance from the strong corona ion source, their outputs were highly correlated (R^2 = 74%) and statistically significant ($p<0.05$) (Figure 4a). A negligible R^2 of 1% was obtained for a 1 second time correlation analysis between particle charge concentration and dc e-field. This correlation improved however when calculated for time averaged measurements, with a maximum R^2 value of 57% ($p<0.05$), obtained for a time average of 4 minutes (Figure 4b). (INSERT FIGURES 4a AND 4b). Real-time (per second) monitoring of aerosol particle number and particle charge concentration levels over a period of one hour, when the P-Trak and AE sampled air at the same distance from the corona ion source, revealed different time series patterns (Figure 5), an observation supported by a statistically low and non-significant correlation (R^2 = 0.6%). (INSERT FIGURE 5)

3.2 Influence of meteorology and source-receptor separation difference.

Overall, wind speed during sampling was from 0 m s^{-1} to 5 m s^{-1}. Results of the measured variation in mean particle charge concentration and dc e-field with respect to wind speed is presented in Table 1. The standard deviation (σ) showed that, for a given wind speed, aerosol particle charge concentration varied widely while the dc e-field remained relatively stable. The results also revealed a very slight initial increase in particle charge concentration and dc e-field, but this increase was not statistically significant ($p>0.05$). (INSERT TABLE 1).

Wind direction during sampling was from within the substation towards the sampling sites, (i.e. 15° to 200° of S_1). As shown in Figure 6a, charged particles sampled by the AE were from 18° to 198° wind direction, while the dc e-field was affected by winds blowing from 33° to 198° (Figure 6b). Results of the analysis also showed that particle charge concentration varied widely within a given wind direction, while dc e-field remained relatively stable. Although high concentrations of charged particles was recorded with wind directions of 53°, 83° and 183°, the entire data set indicated no significant trend could be associated with wind direction. This suggests a high degree of wind instability relative to the dispersion and measurement time. (INSERT FIGURES 6a, AND 6b).

4 Discussions and Conclusions

This paper presents the results of a novel study of the simultaneous monitoring of a number of parameters characterizing the electrical environment of a substantially-constant source of corona ions (transmission voltage substation) which may be used as the basis for other more comprehensive studies in the future. Corona ions emitted by this source were mainly of the negative polarity. The mean aerosol particle charge concentration (-1750 ± 745 ions cm^{-3}) in this environment were found to be statistically significantly higher than that measured in the urban outdoor air (-486 ± 34 ions cm^{-3}) and in a mechanically ventilated room (-84 ± 49 ions cm^{-3}). It was also noted that the release of ions into the environment by the electricity substation was in the form of "bursts" rather than a continuous flow of ions. This was evident from the charge measurement instruments, especially the AE monitoring particle charge concentration (Figures 2b and 6). Hence, both extremely high and low concentrations of ions and charged particles were recorded by the instruments, a trend strongly believed to be responsible for the huge standard deviations recorded, in the study (Table 1).

The presence of unipolar space charges in excess of ambient levels will affect the earth's natural dc e-field. As in the studies conducted in the proximity of HVPLs by Fews et al.

(1999b; 2002) the results of this study also showed that the emitted corona ions caused a significant perturbation of the local dc e-field. Mean negative e-fields, with 2 to 4 fold increase above the local offsite magnitude of 70 V m^{-1} were recorded for distances of 5 m to 27 m from the source. It was also observed that ion concentration and their associated effect on dc e-field decreased with increasing distance from the corona ion source. A similar decrease with distance was recorded in the particle charge concentration. The presence of physical obstructions around the substation however prevented measurements from being conducted to investigate the maximum extent of these observed perturbations, as a function of distance from the corona ion source.

In spite of a six fold difference in their mean values, a statistically strong correlation (R^2 = 74%) was found to exist between ambient ion concentration and aerosol particle charge concentration levels. This difference in magnitude was attributed to the fact that while the AE can sample charged particles in the size range of 0.002 µm to 5 µm, the AIC has the ability to measure a wider range of ions, even down to molecular sizes. The weak linear relationship (R^2 = 1%) found between the instantaneous values of ambient particle charge concentration and the vertical dc e-field was also attributed to differences in the principles of operation of the AE and the e-field meters. With the AE responding to in-situ ion concentrations, the e-field meters have a larger area of detection and are affected by the presence of space charges well away from their location.

Typical airborne particle number concentration levels are usually of the order of 10^3 - 10^5 cm^{-3}, depending on the location and time of day (Morawska et al. 1998). Under the environmental conditions prevalent during this study, the mean particle number concentration (10^3) in the environment of the corona ion source was well within the expected range. In addition, the non-significant correlation obtained between aerosol particle number concentration and net particle charge concentration suggests that their source contributions are different. It may thus be concluded that, although corona ions are released from within the substation, it is not a significant generator of the aerosol particles within the size range (0.02 to 1 μm) determined in this study.

In this particular study, wind speed and direction were not observed to have a statistically significant impact on ion concentration and dc e-field. This could be attributed to the exceptionally high concentration of corona ions emitted by the source, or the close proximity of the sampling instrument to the emitting source. It is suggestive that wind speed and direction may have a more obvious effect at sites with much lower corona ion concentrations or considerable less variation in the emission pattern.

While the results of the study established the existence of associations between some of the parameters (aerosol particle charge and ion concentration; aerosol particle charge concentration and dc e-field) measured in the environment of a substantially strong corona ion source; the absence of any correlation between particle charge concentration and particle number concentration suggests that this ion source is not a generator of aerosol particles within the size range of 0.02 to 1 μm. There is however room for other future and more comprehensive studies to extend the present scope covered in this paper.

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FIGURE CAPTIONS

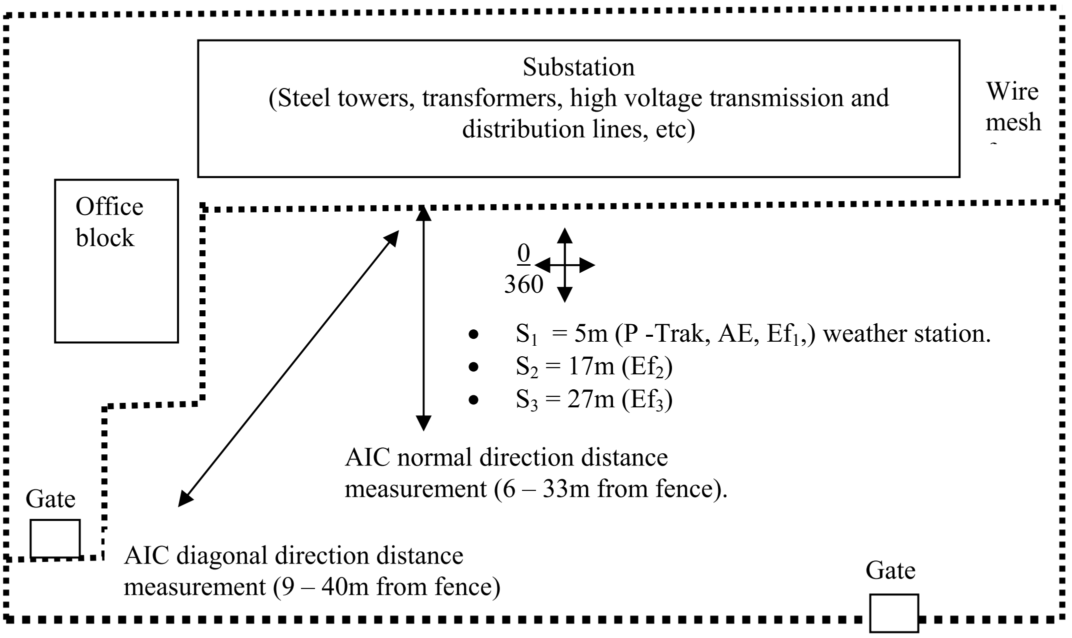

Fig 1: Sampling locations and techniques at the measurement site (not to scale).

AE (aerosol electrometer); Ef$_1$, Ef$_2$ and Ef$_3$ (e-field meters); AIC (air ion counter).

(90^o wind direction represent winds blowing directly from the source to the sampling site; 0^o represented true north, while 270^o represented winds from the sampling site to the corona source).

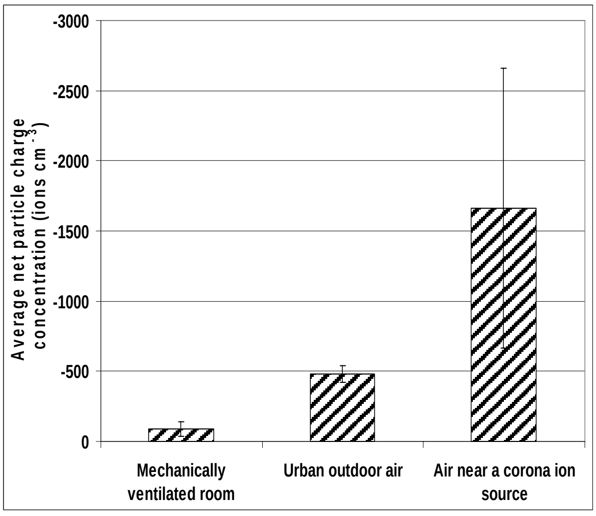

Fig 2a: Mean and standard deviation (σ) of aerosol particle charge concentrations in three different air environments.

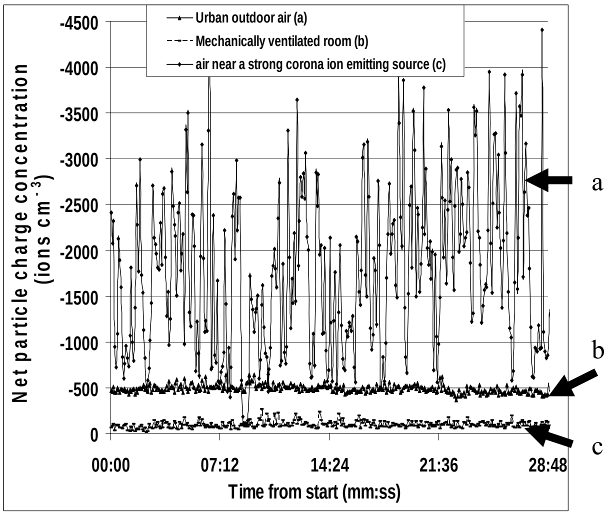

Figure 2b Time series pattern of particle charge concentration in three different air environments.

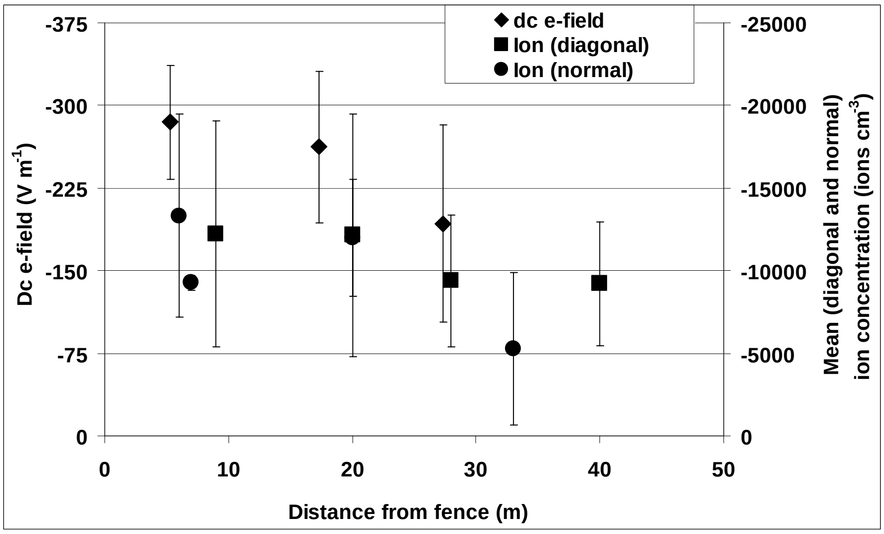

Figure 3: Mean ion concentration and dc e-field measured as a function of distance to the corona ion emitting source.

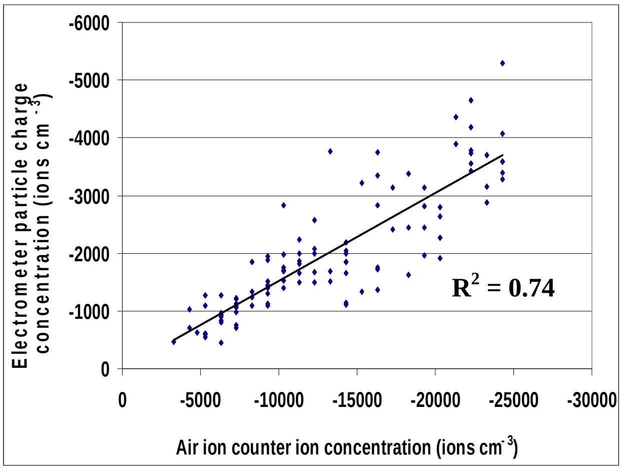

Figure 4a: Correlation analysis of mean aerosol particle charge concentration and ambient air ion concentration.

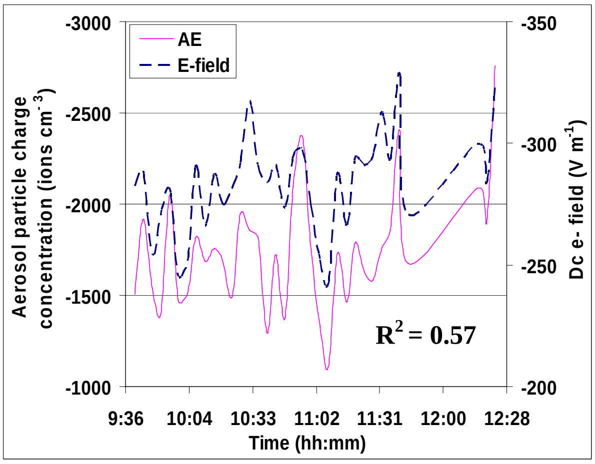

Figure 4b: Temporal variation of aerosol particle charge concentration and vertical dc e-field (averaged over 4 minutes).

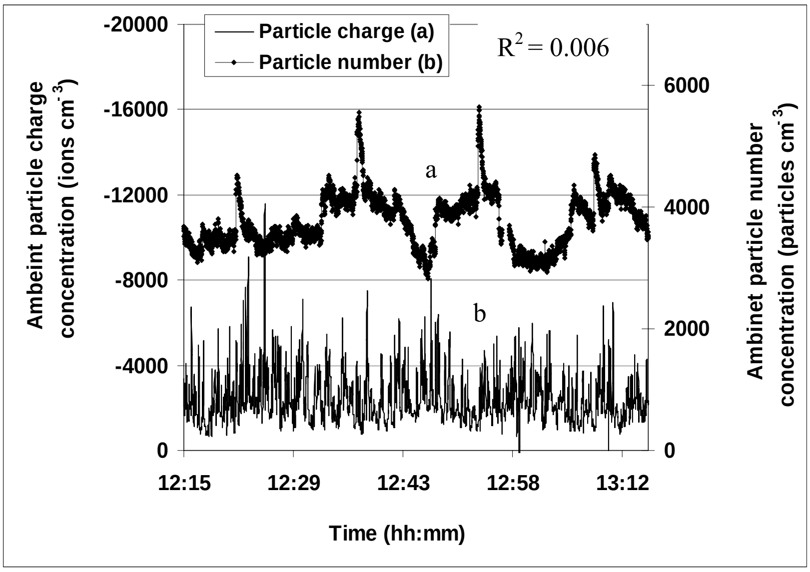

Figure 5 Temporal variation of aerosol particle charge and particle number concentration in the proximity of a strong corona source.

Table 1: Mean particle charge concentration and dc e-field as a function of wind speed.

Wind speed (m s^{-1})	Particle charge concentration (ions cm^{-3})	Change in magnitude of dc e-field (V m^{-1})		
		Ef1 (5.3 m)	Ef2 (17.3 m)	Ef3 (27.3 m)
0.00 – 0.99	-1949 ± 993	-270 ± 60	-246 ± 47	-164 ± 63
1.00 – 1.99	-1843 ± 1587	-277 ± 53	-261 ± 103	-184 ± 82
2.00 – 2.99	-2337 ± 1383	-287 ± 52	-264 ± 56	-182 ± 86
3.00 – 3.99	-1764 ± 994	-288 ± 52	-267 ± 64	-196 ± 103
4.00 – 4.99	-1654 ± 1042	-276 ± 50	-266 ± 57	-179 ± 67

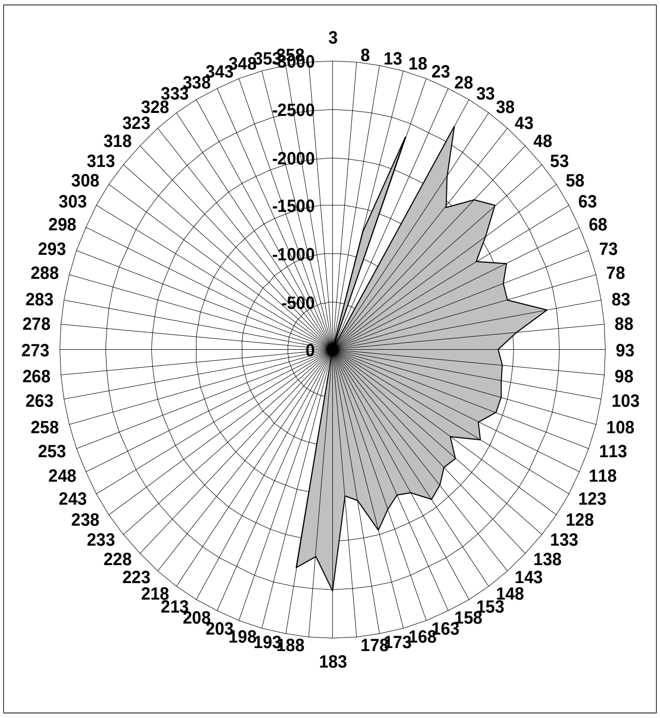

Figure 6a Mean aerosol particle charge concentration (ions cm^{-3}) relative to wind direction (degrees).

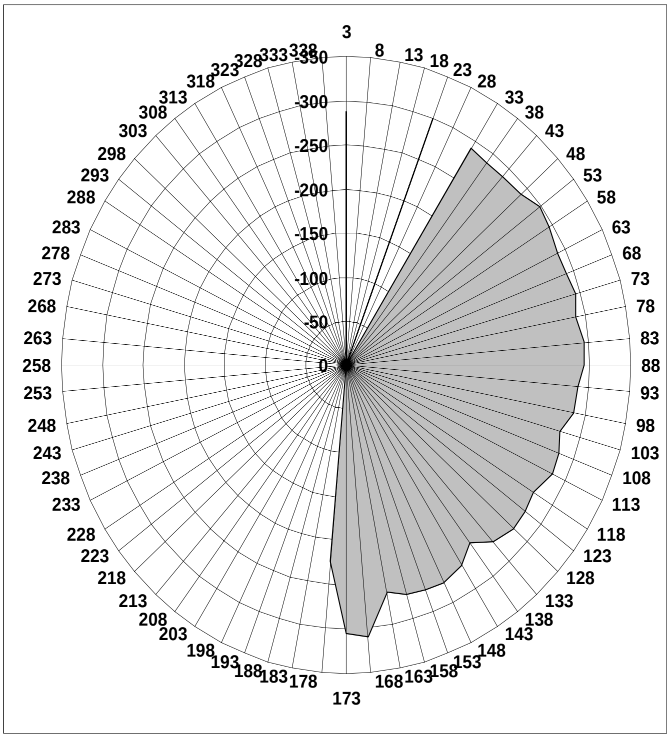

Figure 6b Mean dc e-field ($V m^{-1}$) relative to wind direction (degrees).

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