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The effect of fog on atmospheric electric fields

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Abstract. Naturally occurring electric fields exist in the atmosphere as part of the global electric circuit. These fields are produced by global phenomena, but they are strongly modified by local conditions. One such local effect is fog, which is the reduction in visibility by droplets suspended in the air. For over a century, it has been known that fog can often result in larger values of electric field compared to that in clear air conditions. However, the physical processes controlling the electric field and its variability in fog are still not fully understood. More detailed information on this is required to assess whether electric field measurements can be used as a fog prediction method, which was suggested many decades ago but is still an open question. Furthermore, improving the understanding of electrical processes in fog will also help in related areas of research such as cloud electrification processes and the impact of charge on the behaviour of aerosol and droplets.

This study aims to fully characterise the electric field in fog using an extensive dataset of over 17 years, measured from the University of Reading Atmospheric Observatory, UK. This encompasses electric field, visibility, and meteorological data from over a hundred fog events, which allows us to examine the behaviour of electric fields in fog conditions statistically, rather than only focusing on individual case studies as is often the case in the literature. The long series of data from the site allows the variability in the electrical data during fog events to be more fully characterised than previously.

1. Introduction

Fog is a meteorological phenomenon in which optical scattering by droplets in the air causes the visibility to reduce below 1000 m [1]. Its impacts are especially important to the transportation industry, as the reduced visibility presents difficulty for pilots and drivers to operate their equipment safely, often resulting in loss or damage [2]. However, despite its importance, fog remains a very difficult phenomenon to forecast correctly [3]. It requires a specific set of conditions determined by humidity, radiative environment, wind speed and turbulence, and more. This means that often very small changes in conditions or the local orography can determine whether fog formation occurs, and these are often difficult for traditional numerical weather prediction to capture.

Therefore, it is important to improve our understanding of fog development, including the microphysical, thermodynamic, and electrical processes which dictate its formation.

Fog forms as a result of condensation onto small particles (i.e., dust or salt) suspended in the air when the relative humidity rises above 100%. In other words, droplets condense when the water vapour pressure near the droplet is greater than the equilibrium (saturated) pressure. In inland areas such as Reading, away from large bodies of water, this is typically due to radiative cooling of the surface and low atmosphere at night [2]. This is known as radiation fog, and it is most common in the winter on cloudless and humid mornings before sunrise.

1.1. Atmospheric electricity

Electric fields exist in fog as a result of the global electric circuit. The GEC can be seen as two electrically conductive shells, the earth's surface and the upper level atmosphere near the ionosphere (which is ionized by incoming cosmic rays), which have a weakly conductive layer of air in between [4]. A current is generated across the globe by thunderstorms and electrified rain clouds. Charge separation, a result of collisions between ice crystals and graupel particles in these clouds results in a positive current towards the ionosphere [5]. This creates a potential of around 240 kV between the ionosphere and the earth's surface [4]. The regions of the atmosphere not undergoing charge separation are considered "fair weather," and current flows from the ionosphere back to the surface at these locations [6].

The air is conductive as a result of charge carriers, small ions, which are produced by galactic cosmic rays, as well as radon near the earth's surface [5,7]. Conductivity values are typically around 10^{-15} Sm^{-1} [8]. However, this conductivity can be altered by local weather conditions, such as fog [9]. Therefore, electrical measurements can provide us with valuable information about fog.

Note that the potential gradient (PG), the negative of the electric field, is conventionally used in the discipline of atmospheric electricity, since it is positive upwards in fair weather. The PG (F) can be found from the conductivity σ and vertical current density J_z using Ohm's law:

$$F = J_z/\sigma$$

1.2. PG in fog

The conductivity of air when droplets are present is primarily dependent on the number and size of the droplets. The PG can then be calculated from the conductivity using Ohm's law if the vertical current from the GEC is known. Generally, from this, we should expect the conductivity to drop and the PG to increase during fog.

The conductivity of air is dependent on the number of free small ions. The number of ions can be found by calculating the balance of ions produced (by cosmic rays, etc.) and ions removed from the atmosphere (by recombination and collision with droplets and aerosols). From that, a simplistic equation for the PG (F) in fog can be given by

$$F = J_z \left(\frac{\alpha}{\mu e}\right) \frac{1}{\sqrt{(\beta^2 Z^2 + 4\alpha q)} - \beta Z} \tag{1}$$

where Z is the droplet concentration, β is related to the droplet size, and other variables are constants. (J_z is the vertical current density from the GEC, α is the ion-ion recombination coefficient, μ is the ion mobility, e is the elementary charge, and q is the ion generation term.) See [10] for the derivation of this equation.

From this equation, it can be shown that for an increase in the size or number of fog droplets (both of which occur during fog formation), the PG should increase. This is shown in Figure 1 for in an increase in droplet concentration while droplet size is held constant at 10 μm.

While the theoretical relationship between the PG and fog droplets is relatively straightforward, in the real world, there are many other additional factors which can affect the PG, which will change this relation. In this paper, we will study measurements of PG made in radiation fog in the UK to understand how these affect the overall changes in PG during fog events.

2. Observations of fog

2.1. RUAO dataset

The Reading University Atmospheric Observatory (RUAO) makes routine measurements of meteorological and electrical parameters using digital logging software. Electrical measurements

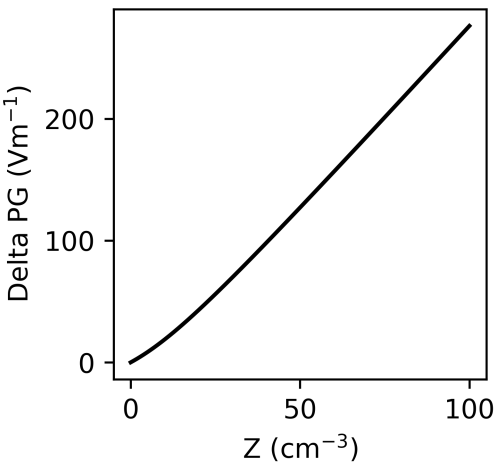


Figure 1: Relationship between change in PG and droplet concentration (Z) for a constant droplet size, from Equation 1.

began in 2005 and continue through 2023; we now have nearly twenty years of fog data available for study. Since 2019, a Biral SWS-250 present weather has measured visibility, which enables direct detection of fog. For the older data, we have developed a method of fog identification from several meteorological parameters.

PG is measured using a Chubb JCI 131 electric field mill, a device which uses a rotating metal plate which alternately shields and exposes two electrodes to generate a difference in induced current to measure the electric field. The field mill is mounted at a height of 3 m, and data logged at 1 Hz.

During the winter of 2022-2023, we deployed a small optical particle measurement instrument, the Light Optical Aerosol Counter (LOAC), to find the fog droplet size distribution, with an approximate size range of 0.1-10 μm. Details of this instrument are described in [11].

For all data, we will be using 5-minute averages in plots and analysis.

In all, we have identified 113 fog events from this time period, which are analysed here.

2.2. Individual events

First, we examine PG measurements from individual fog events.

In Figure 2, we can see a typical case of fog, from February 2023. The event is marked by an initial period of instability in which the fog (indicated with blue shading) comes and goes, before transitioning to a more stable fog later in the night. The PG increases from a typical fair-weather value of just over 100 Vm^{-1} to around 300 Vm^{-1}, over twice the original magnitude, as the conductivity drops.

However, the PG does not remain large. Rather, it varies as the fog conditions change. During the period of stable fog, it is initially large, before it drops off to a lower value eventually.

Figure 3 depicts a fog event from before visibility measurements were made, in March 2012. In this event, the timing of the fog period may not be as accurate, since it is based on meteorological measurements, rather than optical measurements of visibility. However, we see a general agreement between this and other typical fog events, in which the fog is accompanied by a gradual increase in the PG to over 300 Vm^{-1} before another gradual decline after the fog event.

We have also captured data for a fog event when the LOAC droplet measurements were running. This is shown in Figure 4, with several of the size bin concentrations (shown at

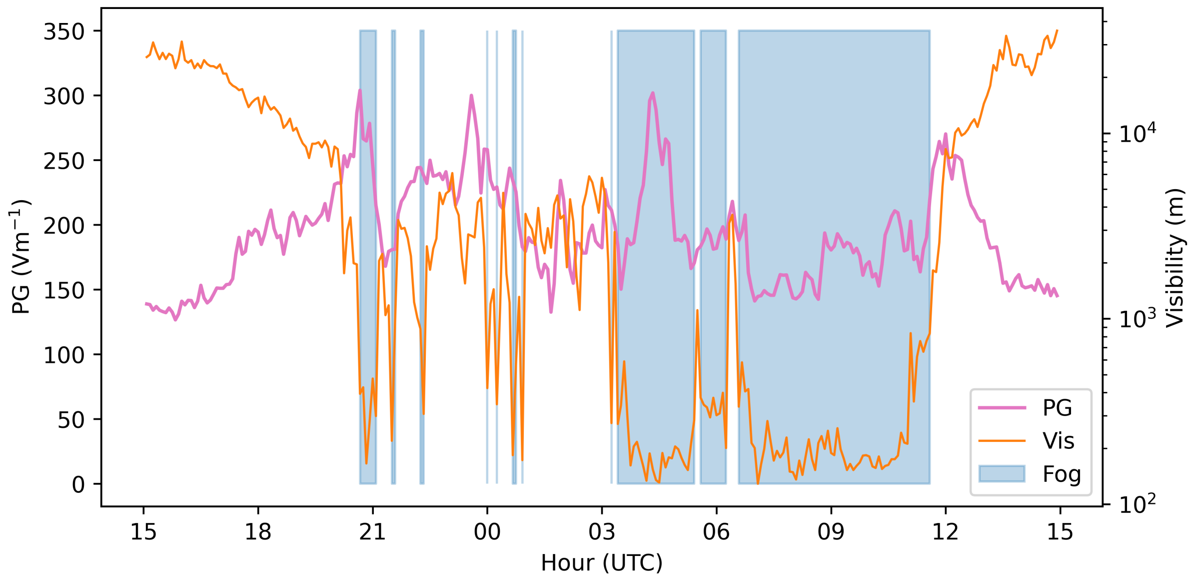


Figure 2: Individual fog event on 8 February 2023. PG (purple) and visibility (orange) are shown, while the regions when visibility are less than 1000 m are shaded blue.

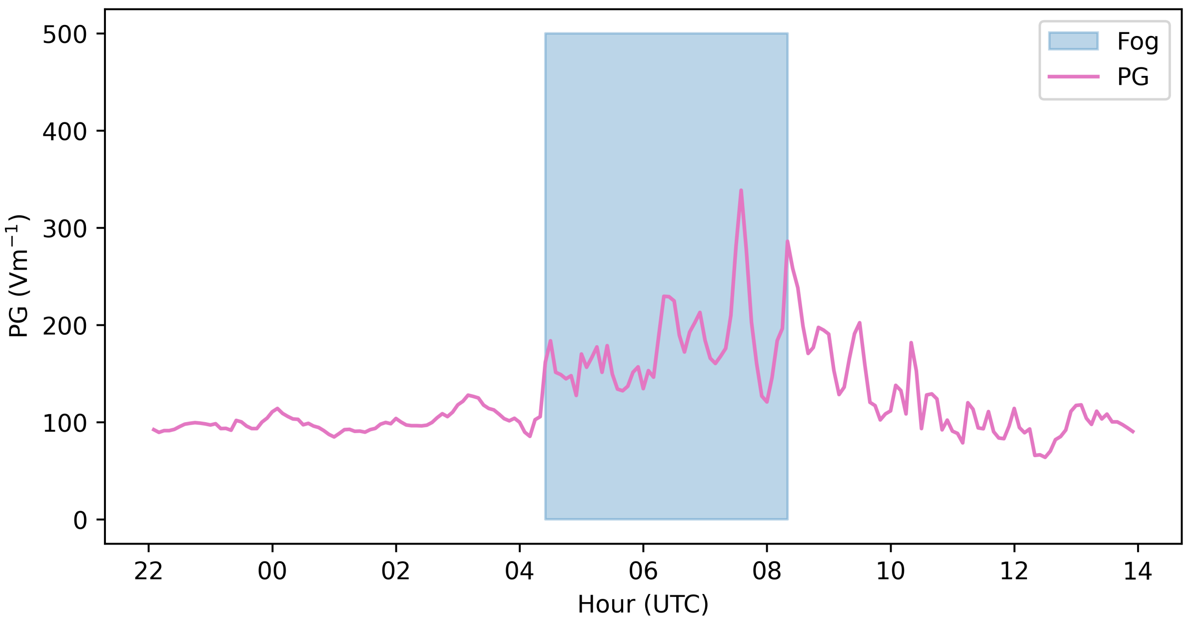


Figure 3: Individual fog event on 12 March 2012. Blue shaded area shows fog detected from other variables including humidity.

different scales for clarity).

In this event, the relationship between droplet size, concentration, and the PG becomes more apparent. Early in the fog event (1800-2200 UTC on the 24th), as the PG increases, we can see a number of small droplets. However, during the thicker portions of the fog (0000-0200 UTC and 0400-0800 UTC on the 25th), we see many more medium-sized (greater than 20 μm) and large (greater than 40 μm) droplets. This also corresponds to a peak in PG values both times

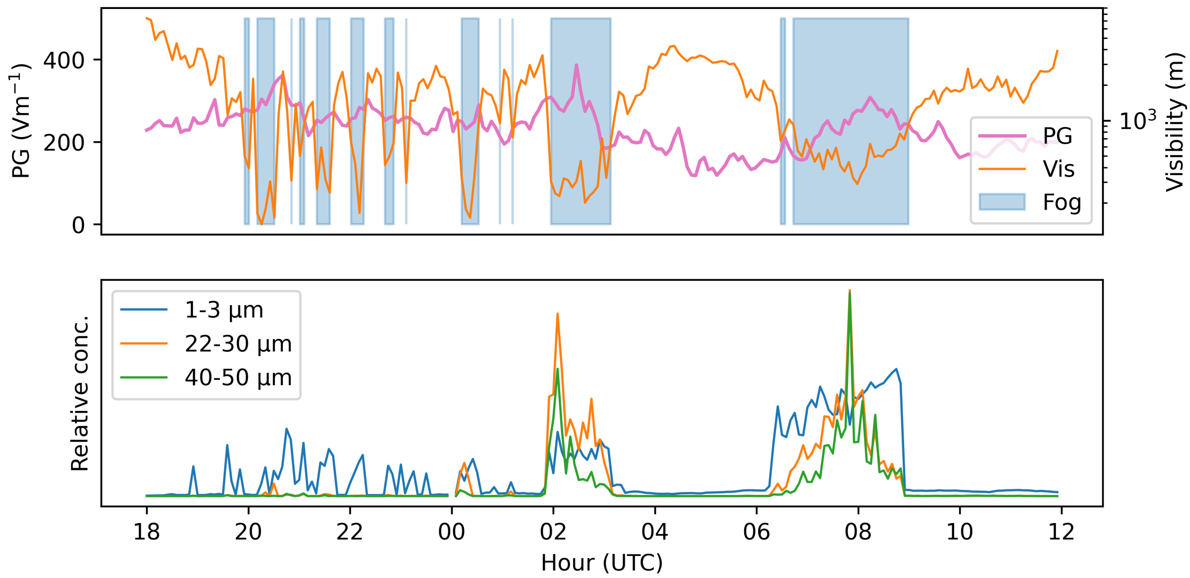


Figure 4: Individual fog event on 25 January 2023. The first panel shows PG and visibility, with fog times shaded in blue. LOAC particle size bin counts (relative) are shown in the second panel, with small droplets in blue, medium droplets in orange, and large droplets in green.

that it occurs. This agrees broadly with the results in Equation 1, since the PG is expected to increase during times with larger and more droplets.

By examining other fog events from the RUAO dataset, we find that the general pattern is for the PG to increase around the time of the fog start. However, the magnitude and timing of that increase varies from event to event. Indeed, in some fog events, there is no noticeable increase above typical fair-weather variation. From this we see that there is significant variation between the electrical environments of different fog events. Further analysis may show how these differences can help to understand the microphysical changes occurring during fog development.

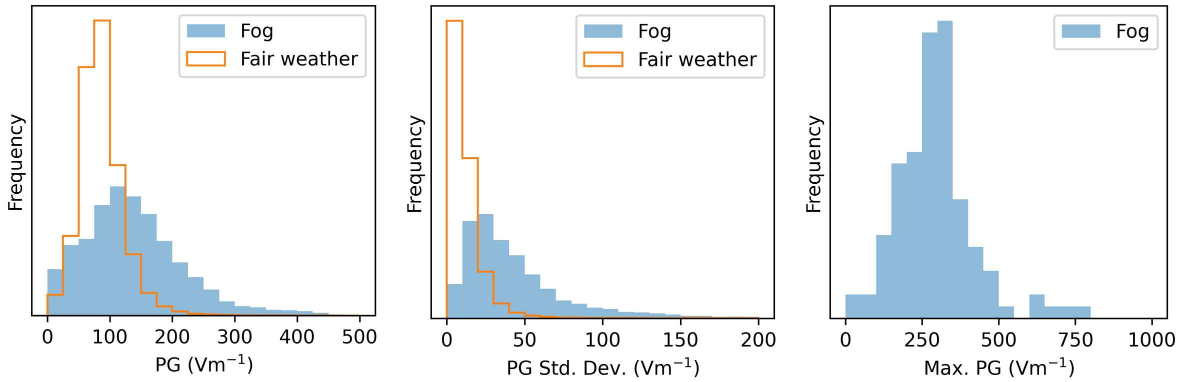
2.3. Distributions of PG values

Besides looking at individual events, it is also enlightening to study the distributions of PG measurements across all fog events. The measurements for fog and fair-weather cases are compared in Figure 5.

In Figure 5a, we can see that the PG values are generally larger during fog events compared to fair weather conditions (defined as wind speeds between 1 and 8 ms^{-1}, no negative PG, and no rain or fog). The median increases from 82 Vm^{-1} in fair weather to 120 Vm^{-1} in fog. However, there is also some overlap between the two distributions, as there is a significant fraction of fog measurements under 150 Vm^{-1} and some non-fog measurements reaching higher values over 200 Vm^{-1}. However, we can see that PG measurements exceeding 300 Vm^{-1} are much more common in fog than in other conditions, which agrees with the expectations.

From Figure 2 and Figure 3, it is apparent that the variability in PG during fog is often increased compared to normal fair-weather values. We have therefore also examined the variation in PG during fog. Figure 5b shows the standard deviation which also increases during fog (the median changes from 9 Vm^{-1} to 36 Vm^{-1}). This increase in variability is expected to be a result in variation in the thickness of the fog, as well as possibly motion of fog droplets under turbulence, which could result in variable space charge.

Finally, the distribution of maximum PG values for each fog event is shown in Figure 5c. We



(a) PG values (b) PG standard deviation (c) Maximum PG per event

Figure 5: Histograms of PG measurements in fog and fair-weather conditions

can see that the majority of events are consistently less than 500 Vm^{-1}, although a few fog events increase above this. There are also several fog events (under 10%) in which the maximum PG is comparable to normal fair-weather values (i.e., less than 150 Vm^{-1}), as mentioned in Section 2.2.

3. Conclusions

This paper discusses an investigation into the effect of fog on electric fields, based on a large dataset with over a hundred detected fog events.

The results broadly agree with the accepted physical basis for a change in PG during fog events. Generally, the PG increases gradually with the onset of fog. However, it is clear from the distributions of PG and PG variation that these values are also regularly similar to fair-weather values, which would prevent a clear discrimination between fog and fair weather based solely on PG measurements.

Measurements of droplet spectra shown here have provided further evidence for the presented theory on PG during fog. During one of the case studies presented here, the PG was measured to increase during the time in which small droplets prevailed, while additional maxima in the PG were associated with times with medium and larger sized fog droplets. This emphasises the importance of simultaneous measurements of droplet properties, meteorological parameters, and electrical parameters, in order to more fully understand the behaviour of PG in fog and whether it can be used as a potential fog forecasting tool.

Acknowledgments

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