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Ahmad A.Alkamali[1,2], Maarten H. P. Ambaum[1] & Keri A. Nicoll[1]

1. Department of Meteorology, University of Reading, United Kingdom
2. Department of Research and Weather Enhancement, National Center of Meteorology, United Arab Emirates

Abstract

Distinct differences in electrical characteristics of the atmosphere are observed during clear and foggy laden air. The presence of droplets in the air causes the removal of natural cluster ions and hence, a change in the electrical properties, which is useful for fog detection, and potentially fog forecasting. In this study, we report on some of the first electrical measurements conducted during fog in the United Arab Emirates (UAE).

The analysis indicates that the Potential Gradient (PG) values observed during fog in the UAE were substantially higher than those previously reported in the literature (ranging from -1247 V/m to 1400 V/m). Furthermore, the PG during fog was often negative, with 93% of cases recording negative PG values (with median PG value of -397 V/m), particularly during wintertime fog events. A comparison with fog measurements conducted in the UK showed a stark contrast in PG behaviour between the two sites, with only positive PG values reported during fog in the UK (as is the case for the majority of PG fog studies reported in the literature), and higher PG variability in the UAE fogs. It is hypothesized that the unusual polarity of PG observed in UAE fog events may be attributed to the deposition of fog droplets, during which positive charges are transported from the top of the fog layer downwards toward the surface, thereby modifying PG. This deposition process is expected to be particularly active during the latter stages of the fog, when the droplet size distribution has fully evolved.

Keywords:

Fog
Potential Gradient
Atmospheric Electricity
United Arab Emirates

1. Introduction

A continual electric field occurs in the atmosphere due to the presence of Earth's Global Atmospheric Electric Circuit (GEC). The GEC describes large scale current flow around the planet, caused by charge separation in thunderstorms, which generate a large potential difference between the conductive upper atmosphere and Earth's surface (Wilson, 1921). Measurements of atmospheric electricity can provide valuable information about the local meteorological conditions close to the observation site, including warning of disturbed weather, lightning, and fog formation (Nicoll, 2012). The most frequently observed surface quantity in atmospheric electricity is the vertical electric field, which is measured as the Potential Gradient[1] (PG) (Bennett and Harrison, 2007).

The PG is closely related to local air conductivity, which originates from the presence of atmospheric cluster ions. Natural ionisation, produced by galactic cosmic rays and Earth's surface radioactivity, is the main cause of the finite electrical conductivity of air. Both positive and negative air conductivities are strongly influenced by the presence of aerosol and water droplets (Bennett and Harrison, 2008; Bennett and Harrison, 2009). Such aerosols include different particle sizes, which can affect PG by reducing the mobility of the ions through attachment, particularly to the larger particles (Yair and Yaniv, 2023), and consequently, removing the natural background small ions. The reduction of ion number concentration results in a decrease in air conductivity. As a result, the PG increases as the air conductivity decreases. The PG and air conductivity (σ) are related by Ohm's law:

$$J_z = \sigma \, PG \qquad (1),$$

where J_z (which is assumed to remain constant) is the vertical conduction current density, which flows as a result of the GEC (Rycroft et al., 2000).

Many studies have reported the marked difference in PG between fair[2] and disturbed weather (Dolezalek, 1973; Hoppel et al., 1986; Anisimov et al., 2005; Bennett and Harrison, 2009; Harrison and Nicoll, 2018). During fair weather conditions, the observed PG is normally positive with typical values ranging between 50 to 300 V/m depending on the site (Bennett and Harrison, 2007). In addition, the magnitude of PG variability during fair weather conditions is low when compared to that observed during disturbed weather conditions. However, the presence of aerosol concentrations in the air can cause substantial changes in PG (Bennett and Harrison, 2008).

[1]Potential Gradient (PG) is the difference in potential between the surface and a fixed point vertically above it, which is often used instead of the electric field (E) but with the opposite polarity (i.e., PG = -E) (Harrison and Nicoll, 2018).

[2]Fair-weather: For the conditions to be classified as "fair-weather", the Met Office (in 1964) required four criteria, which are: (1) hours with no hydrometeors (i.e., no rain, hail, snow). (2) no low stratus clouds. (3) less than three eighths cumuliform clouds. (4) mean hourly wind speed less than 8 m/s (Harrison and Nicoll, 2018).

Fog occurs due to the condensation of water vapor to form droplets, which become suspended in air, leading to a reduction in visibility (typically defined as visibility less than 1 km). During fog, the PG is generally observed to increase substantially and become more variable. Harrison and Nicoll (2018) provided a good example of a foggy event observed in Reading, UK. A clear change in PG during the fog incident was reported, where the PG increased from about 150 V/m to 200 – 250 V/m and became more variable. As the fog starts to dissipate, the PG decreased until it reached a steady value of 100 – 150 V/m, where the fog has completely dissipated.

A further comparison between foggy air and fair weather conditions was performed by Bennett and Harrison (2009). A clear difference was reported between the two conditions, where the measured PG was 400 V/m during fog while 100 V/m was observed during fair weather. The ratio of PG between foggy air and clear air can be obtained from Ohm's law assuming the fair weather current from the ionosphere to the surface is broadly constant across a fog event. This ratio of foggy air PG to clear air PG is only applicable with respect to the vertical conductivity, giving:

$$\frac{PG(Fog)}{PG(Clear\ air)} = \frac{\sigma\ (Clear\ air)}{\sigma(Fog)} \qquad (2),$$

The presence of water drops and other aerosols leads to scavenging of free cluster ions that are responsible for the conductivity of the air (Harrison and Ambaum, 2008). As a consequence, foggy air exhibits lower conductivity compared to clear air.

Understanding the physics of fog has been a topic of significant interest due to its societal impact, particularly in terms of negative effects on transportation. Despite significant advances in numerical forecasting of fog during the past few decades, accurate fog prediction is still a challenge (e.g., Roman-Cascon et al., 2016). Previous research (Serbu and Trent, 1958; Dolezalek, 1973) has suggested that atmospheric electrical measurements may be useful for fog prediction, but this is still very much an open research question. Interest in the electrical properties of fog is also motivated by understanding the effect of charge on the behaviour of fog droplets (Harrison et al., 2022), with applications in fog dissipation (Tag, 1976; Zhang et al., 2023), and collection of fog droplets for water harvesting (Li et al., 2022).

This paper aims to characterise the electrical properties of fog in the United Arab Emirates (UAE) via a new dataset of atmospheric electrical observations. The measurement site is a desert location, where fog is prevalent during the winter months. Few papers in the literature report on fog observations from desert sites, so this is one of the first to characterise the electrical properties of fog in the desert. In this paper, Section 2 discusses the observation sites and instrumentation used. Section 3 reports observations of PG and meteorological parameters during several fog case studies, followed by a statistical analysis of all fog events captured in the UAE dataset. In order to compare the PG in fog in the UAE with those typically observed at mid latitude sites (which dominate the literature), Section 4 compares the UAE observations with those from a mid-latitude site in Reading, UK. The relationship between PG and visibility in the UAE and Reading is also considered in Section 4. Section 5 presents a discussion and Section 6 the conclusions.

2. Observation sites and instrumentation

The data presented in this paper is from a new observation site at Sanad Academy, Dubai, UAE (24° 56′ N, 55° 30′ E), which was established in February 2021. The UAE (where the most prevailing aerosol type is composed of mineral dust (Nelli et al., 2021)) experiences frequent fog events throughout the year, with the highest frequency during the autumn and early winter months (de Villiers and van Heerden, 2007). This depends mainly on the sea-land breeze, which happens on over 70% of days during winter months in the UAE (Eager et al., 2008). The process starts with a transport of moisture from the sea during the day with the sea-breeze, which can extend up to 200 km in land. During night time, the wind veers towards the land due to the temperature gradient caused by rapid cooling of air and hence, weakening the sea-breeze. A land breeze is common overnight in the UAE, which often lasts into the early morning and persists until the sea-breeze forms (Eager et al., 2008).

The most common fog type observed in the UAE is radiation fog (Weston et al., 2021), where the land cools rapidly at night and in turn causes the air above it to cool. As a result, water vapor condenses into liquid droplets and fog forms.

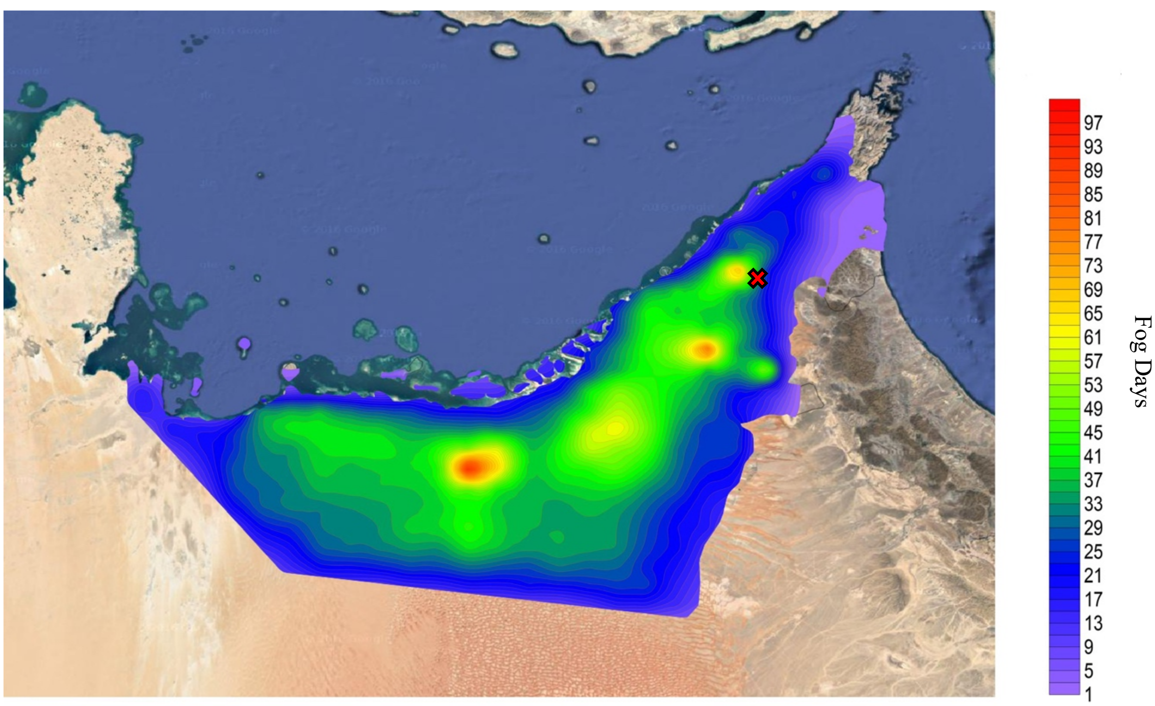

Figure 1. Annual number of fog days in the United Arab Emirates (UAE) for the year 2021. The location of the selected field site (Sanad Academy) is marked as red cross. This figure was obtained from the National Center of Meteorology (NCM), UAE, using data from NCM's automatic weather stations across the UAE, along with EUMETSAT infrared satellite images.

As the fog occurs, the horizontal visibility drops, which has historically led to significant economic losses in the UAE. These losses include transport disruptions such as air traffic delays, and car traffic accidents (Ali et al., 2013; Mohan et al., 2020). Figure 1 displays the number of fog days in the UAE during 2021, where most cases were observed in the internal regions of the country (ranging between 30 – 60 fog days) and some locations witnessed almost 100 fog days in 2021. This distribution of fog occurrences is typical for most years in the UAE. At Sanad Academy (marked as red cross in Figure 1), 27 fog days (both light and dense fog) were observed during 2021. Dense fog cases were identified as cases when the visual range was ≤ 1 km for at least one hour period, while light cases (i.e., mist) were characterised by visibility ranges >1 km and ≤ 3 km. Additionally, a relative humidity (RH) >90% was used as a supplementary indicator to distinguish fog from the presence of other aerosols.

The measurement mast at Sanad Academy is located in the internal desert region of Dubai, which is a favorable location for radiation fog formation. As a result of radiative cooling, the air over the desert cools rapidly during the night, which causes the sea-breeze to weaken, leading to a reduction in the effects of warm maritime temperatures. As the surface radiative cooling intensifies, a surface inversion forms which traps the moisture near the surface and eventually, extends vertically until the dewpoint temperature is reached, where fog can form (Weston et al., 2021).

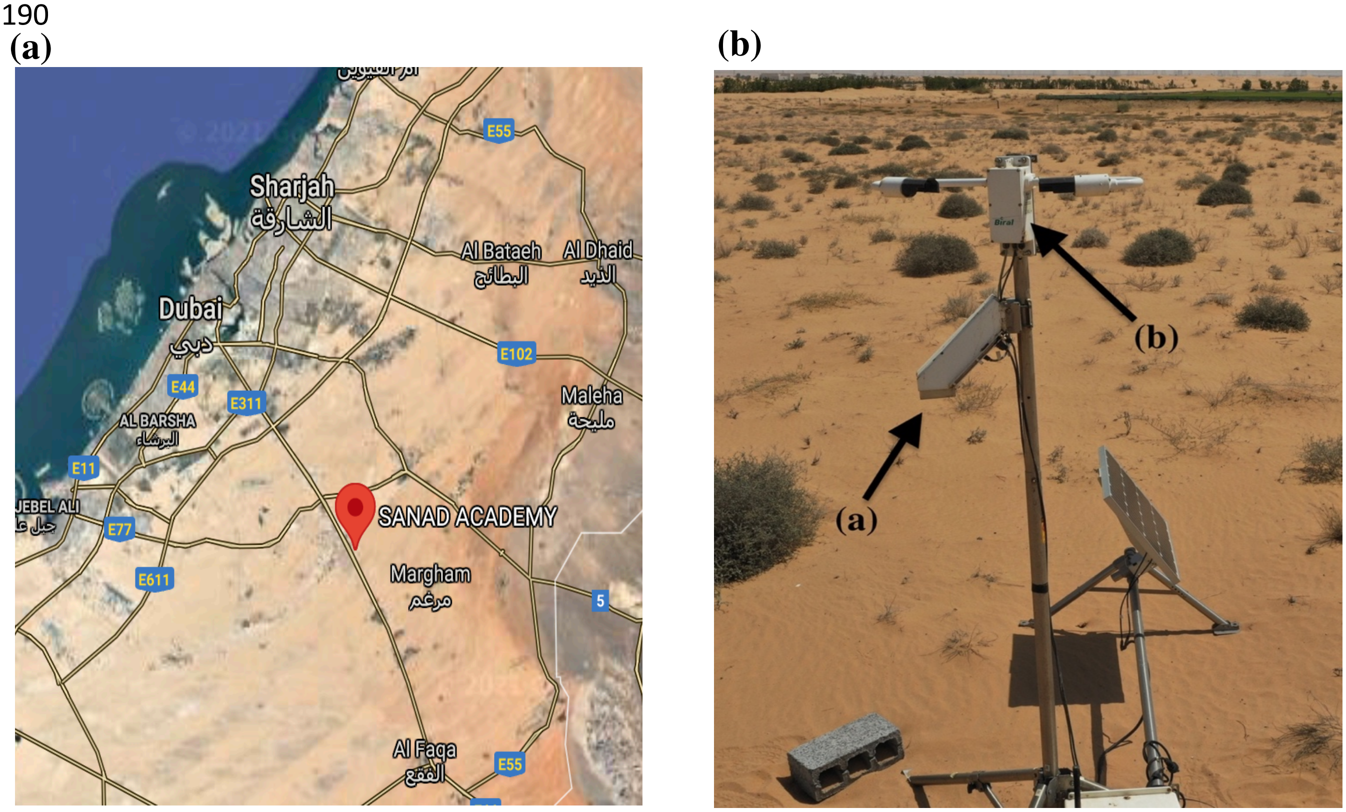

Figure 2. The location of the observation site and instrumentation used. (a) Map of the UAE displaying the location of Sanad Academy, Dubai (obtained from Google Maps), and (b) sensors used to conduct this study, including (a) A downward facing electric field meter (Campbell CS110), used to measure the PG, and (b) The visibility sensor (Biral SWS-100).

Atmospheric electrical observations were conducted at Sanad Academy since February 2021 to present. Sanad Academy is an unmanned aircraft training facility in a desert location (approximately 45 km from the coastline), with the electrical instrumentation mast mounted on a sandy surface. The closest buildings to the instrumentation are 400 m away. Figure 2 display the location of the field site along with the instrumentation used. Instrumentation includes a Campbell CS110 electric field meter to measure the PG and Biral SWS-100 visibility sensor to measure the horizontal visibility. The CS110 was mounted at a height of 3 m above the ground, with a measurement range of ±20 kV/m, at a sampling rate of 1-second. PG data were averaged, to 1-minute mean values to conduct the analysis described in this study. The visibility data were logged at 1-minute time resolution. Detailed explanation of the instrumentation used is given in Appendix A.

Meteorological data are also analysed in this paper, obtained from Al Marmoom Automatic Weather Station (AWS), Dubai (25° 00′ N, 55° 30′ E). Meteorological observations include air temperature, RH, wind speed and direction, all logged at 15-minute time resolution. Al Marmoom is located approximately 9 km northeast of Sanad Academy (about 36 km from the coastline). The AWS used here is part of the National Center of Meteorology (NCM), Abu Dhabi, UAE. Due to the homogeneity of the terrain and the proximity, the weather conditions at Al Marmoom generally closely match those observed at the Sanad Academy field site.

The observations in the UK were conducted at Reading University Atmospheric Observatory (RUAO), Reading (51.441° N, 0.937° W). The observations were performed from December 2020 to January 2021. At the site, a JCI131 electric field mill was used for PG measurements and a Biral visibility sensor to measure the visual range during the observation period. PG and visibility data were logged at 5-minute time resolution.

3. Electrical characteristics of fog in the UAE

The following section presents two individual fog case studies from Sanad Academy, UAE, followed by a statistical analysis of all fog events from the Sanad Academy dataset. For an event to be classified as fog, the horizontal visibility must drop below 1 km as described in previous studies (Mohan et al., 2020; Tardif and Rasmussen, 2007; Weston et al., 2021) along with high RH which typically exceeds 90 %, this criterion is applied here to define fog events.

Figure 3 presents data for the first fog case study on, March 31st, 2021, with PG and visibility (plotted on logarithmic scale) in Figure 3 (a), wind speed and direction in Figure 3 (b), and RH and temperature in Figure 3(c). During this day, several different types of meteorological conditions were observed at Sanad Academy which affected the PG, including early morning fog, an afternoon sea breeze front and a change in airmass in the evening, each of which is discussed in turn. Figure 3 (a) demonstrates high visibility (≥ 10 km) and fair weather values of PG (~200

V/m) from 00-02 LT (UTC+4), in the period before fog forms. For comparison, the average typical diurnal variation in PG and visibility under fair weather conditions is displayed in Appendix A.2. As the condensation of haze droplets begins, the PG becomes negative, decreasing sharply down to -400 V/m at about 03 LT. This is followed by a steep decrease in visibility (down to 90 m) approximately an hour later (at 04 LT). Consequently, the dry bulb temperature was very low (about 16°C) and the RH was very high (reaching up to 100%), confirming the presence of a dense fog event. During the established fog period (04 – 07 LT) the PG is variable and mainly negative and fluctuates between 150 and -150 V/m. The existence of such negative PG values during fog is unusual, being rarely reported in the literature, and seem to defy theory, which predicts that a decrease in conductivity in fog should lead to an increase in PG (e.g., Harrison, 2012). This will be discussed further in Section 5.

Following dissipation of the fog event around 07 LT, the afternoon of March 31st experienced a sea breeze, as shown in Figure 3. This is characterised by abrupt change in PG between 14 to 16 LT, where the PG increased from 200 V/m up to 1000 V/m. During the same time, visibility decreased to 10 km, the wind speed increased from approximately 3 m/s to 6.5 m/s, and the wind veered from SE-SW and began blowing from W-NW (275° – 300°). These changes signify the arrival of the sea breeze front, which occurs due to temperature contrast between the land and the sea (Miller et al., 2003), a common phenomenon in the UAE (Eager et al., 2008). The large transient increase in PG during the sea breeze is characteristic of that reported in Nicoll et al. (2020) at another site (Al Ain international airport) located in the southeast of the UAE, and is thought to be associated with lofting of charged aerosols in the sea breeze front. During 2021, a total of 125 days of electrically active sea breeze cases were observed at Sanad Academy from a total of 238 days of data.

In Figure 3 (a), the final distinct change in PG happened from about 21 – 00 LT, where a sudden decrease and polarity reversal in PG (from 200 V/m down to -200 V/m), occurs as well as an increase in the PG variability. Correspondingly, the visibility dropped from 10 km to 8 km. This sudden reduction in PG appears to be correlated with wind direction veering from NW to SE (300° to 135°), and also a decrease in wind speed from 6m/s to 1m/s. This shift in wind direction may indicate the change from a sea breeze to a weak land breeze, which would likely alter the aerosol properties over the measurement site. Sensitivity of the PG to wind direction was reported by Bennett and Harrison (2007), who found that variations in charged aerosol concentrations associated with wind direction changes, cause marked alterations in the PG. However, further analysis is still required to confirm the cause of the PG variations during this period.

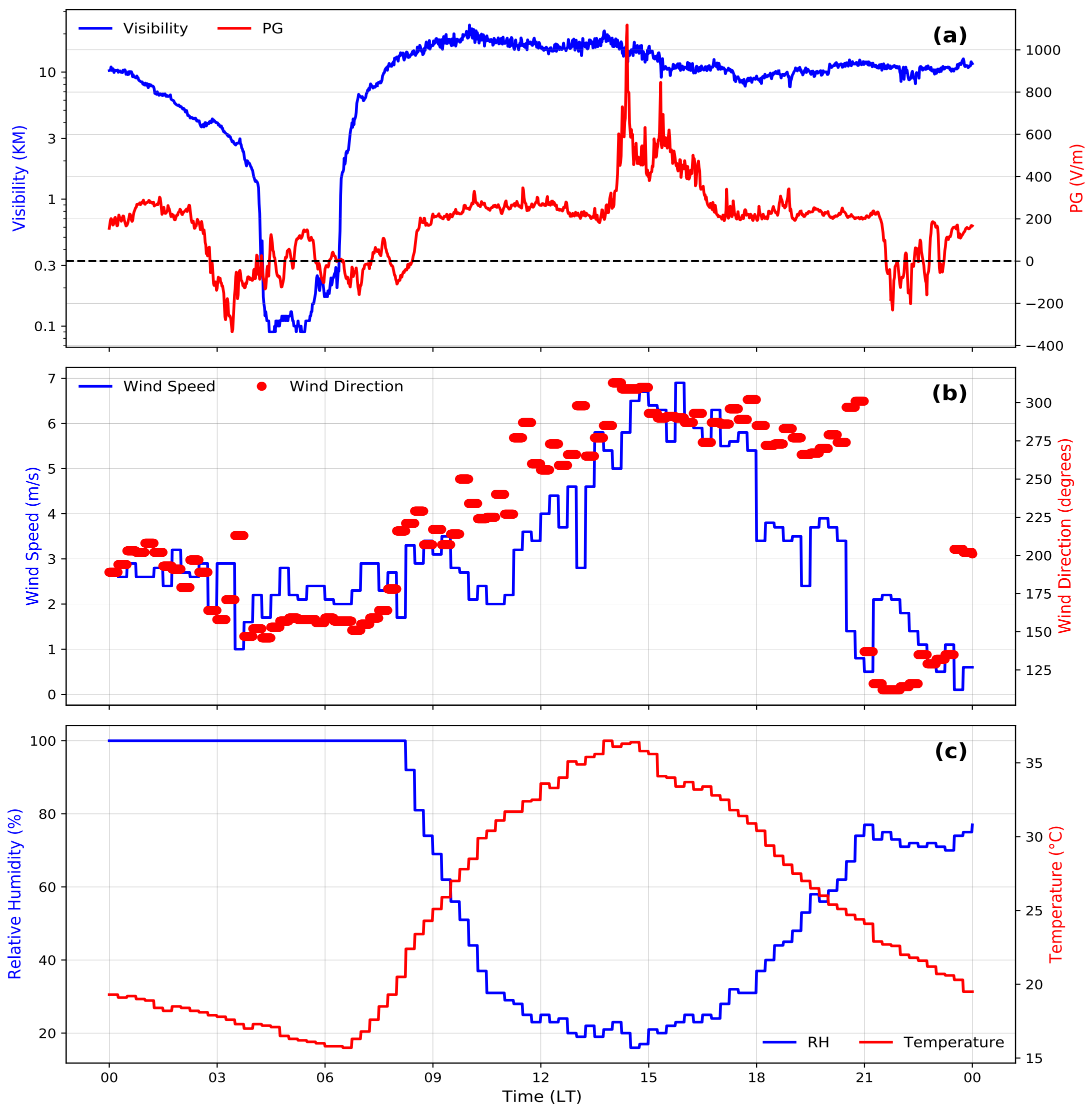

Figure 3. Diurnal variation in (a) PG and Visibility at Sanad Academy, (b) Wind speed and direction, and (c) Relative Humidity (RH) and Temperature from Al Marmoom AWS. The timeseries ranged from 00 UAE LT March 31st, 2021 till 00 UAE LT April 01st,2021. PG and visibility are 1-minute time resolution while the wind speed and direction, RH and temperature are 15-minute time resolution. The wind direction was omitted for wind speeds of 0 m/s. The visibility data are presented on a logarithmic scale.

A second fog case study was observed on April 07th, 2021, presented in Figure 4. Similarly, as in the first case study presented in Figure 3, the fog event occurred during the early morning hours (04 – 07 LT) and was followed by a sea breeze event during the afternoon (14 – 18 LT). Figure 4 (a) shows a gradual decrease in visibility from 00 – 04 LT as haze starts to form, followed by a sharp decrease in visibility from 1 km to 60 m around 04 LT as the fog becomes more established. This fog case was further confirmed by the RH observation exceeding 95 % as seen in Figure 4 (c). The PG shows a small increase during the haze phase (from 100 – 300 V/m), but then decreases gradually from 04 LT as the fog forms. A sharp decrease to large negative values (-1100

V/m) is observed at 07 LT approximately 30 minutes before the fog dissipation (as indicated by the increasing visibility at 08 LT, and a temperature rise from 14°C to 20°C). Although the visibility has increased to non-fog values by 0830 LT the PG remains large and negative until 0900 LT. During the dissipation period, the fog droplets start to evaporate, but it takes some time for the air to become entirely droplet free (and also any charge that existed on the fog droplets will remain in the air). Thus, we expect it to take some time for the PG to return to its normal background value after the fog dissipation stage. One of the distinctions between the two case studies is that the largest change in PG in Figure 4 is approximately 1-2 hours following the fog formation (identified from the reduction in visibility), whilst in Figure 3, the largest change in PG occurs at the start of the fog event. The reasons for these discrepancies are still unclear.

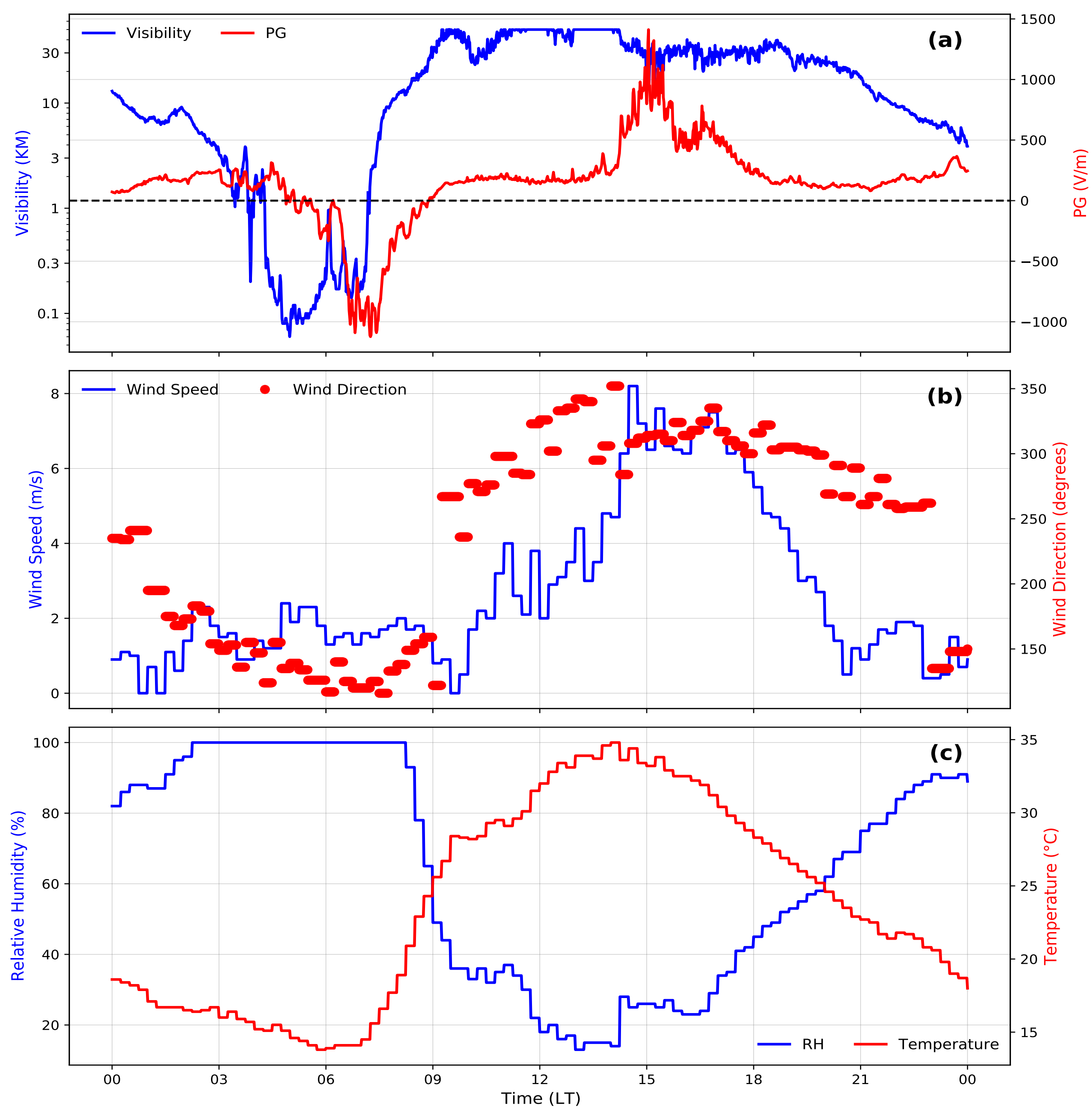

Figure 4. Diurnal variation in (a) PG and Visibility at Sanad Academy, (b) Wind speed and direction, and (c) Relative Humidity (RH) and Temperature from Al Marmoom AWS. The timeseries is from 00 UAE LT April 07th, 2021 till 00 UAE LT April 08th,2021. PG and visibility are 1-minute time resolution while the wind speed and direction, RH and temperature are 15-

minute time resolution. The wind direction was omitted for wind speeds of 0 m/s. The visibility data are presented on a logarithmic scale.

As in Figure 3, the arrival of an afternoon sea breeze front is evident in Figure 4, where the PG increases rapidly from 200 V/m to 1400 V/m between 14 – 17 LT. During this period, visibility reduces from 50 km down to 15 km and wind speed increases to 8 m/s, with a directional shift from SE to W-NW.

Both case studies in Figures 3 and 4 demonstrate that the PG during fog conditions in the UAE is often large and negative, in contrast to most of the results reported in the literature (which are predominantly large and positive) (e.g., Serbu and Trent, 1958; Dolezalek, 1973; Yaniv and Yair, 2023). To establish whether this type of PG behaviour is dominant during fog events in the UAE, statistical analysis of more fog events is required. From the Sanad Academy dataset, we have identified 27 fog events during 2021. 19 of these events were classified as dense fog (defined as cases when the visibility is ≤ 1 km with RH >90 %) and 8 classed as mist cases, where the visibility was greater than 1 km and less than or equal to 3 km and RH observations exceeding 90%. Only 2 of the fog events occurred during the UAE summer months (June – August), with 25 events during winter/spring (February – April).

Figure 5 displays the distribution of maximum positive PG, maximum negative PG, minimum visibility, and fog duration observed at Sanad Academy during all 27 fog events in 2021. Of the 27 fog events, the largest maximum positive PG recorded was 1318 V/m (median = 311 V/m), which was observed during a summer fog event (both summer fog events exhibited only positive PG values, with values > 1000 V/m in both events). This is large compared to most reported measurements of PG during fog in the literature (typically 300 – 800 V/m). Figure 5 (a) also demonstrates that in some of the fog events (2 events) the maximum PG is negative, and this occurs in both fog and mist cases.

From Figure 5 (b), most PG values were clustered below 0 V/m (median = -397 V/m), with the lowest recorded negative PG value during fog events being -1247 V/m. This overall tendency towards negative PG was observed in 25 of the 27 fog events (93%), and predominantly during winter fog events. From the minimum visibility distribution in Figure 5 (c), it is apparent that approximately 70% of the fog events were classified as dense fog events, in which the lowest visibility recorded was 20 m (with median = 250 m). The winter fog events experienced lower visibilities in comparison to the summer fog events (with the minimum visibility in summer fog being 170 m).

Figure 5 (d) shows the duration of the fog events, in which the median fog duration was 5 hours (comparable to other UAE fog events reported in the literature, such as Mohan et al., 2020), and the maximum duration observed was 10 hours. The two summer fog events exhibited much shorter durations, typically only lasting 1 hour.

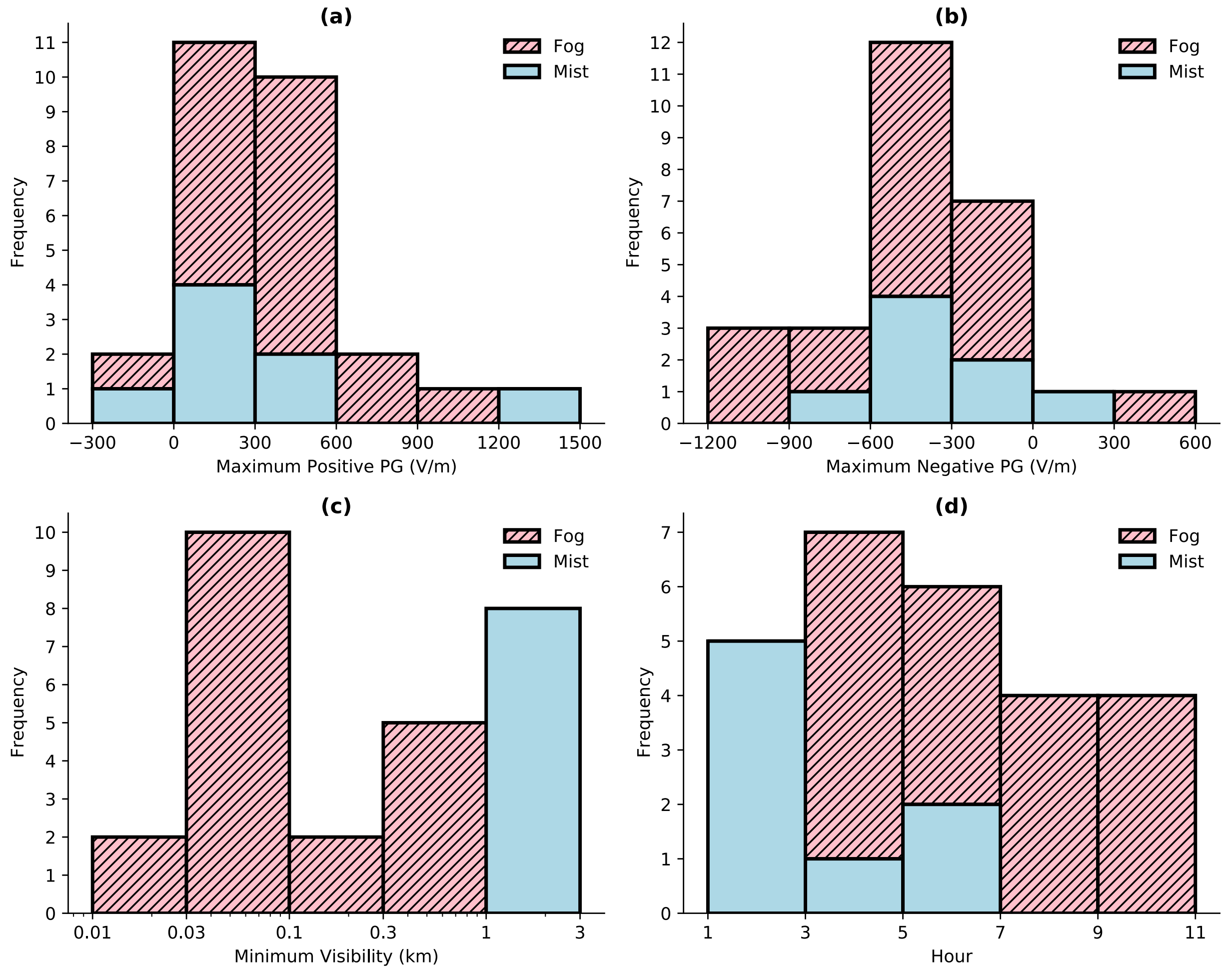

Figure 5. Stacked histograms of (a) maximum positive PG, (b) maximum negative PG, (c) minimum visibility, and (d) fog duration, during 19 dense fog events and 8 light fog events at Sanad Academy in 2021. Fog events were defined as instances when visibility was ≤ 1 km, while mist events were characterised by visibility >1 km and ≤ 3 km (with RH >90% in both conditions). Minimum visibility data are presented on a logarithmic scale.

4. Comparison of electrical characteristics of fog at different sites

4.1 United Kingdom case study

In the preceding section, the electrical properties of fog in the UAE were investigated. In this section, a comparative analysis is undertaken to assess the electrical characteristics of fog in the UAE in relation to those observed at a typical midlatitude site, chosen to be Reading, UK. Generally, the UAE exhibits significantly higher aerosol loading in comparison to the UK, which has much more rainfall, more grass covered sites and, hence, lower aerosol loading (Nicoll et al., 2022). This discrepancy in background aerosol loading between the two countries potentially contributes to large differences in the observed electrical properties, which we seek to investigate. For this analysis, a fog case study from Reading is examined, followed by a comparison of statistical fog properties between the UAE and Reading sites for a small number of fog events. A timeseries of the meteorological and electrical parameters during a typical fog event at RUAO, UK is displayed in Figure 6 between December 31st, 2020 and January 01st, 2021.

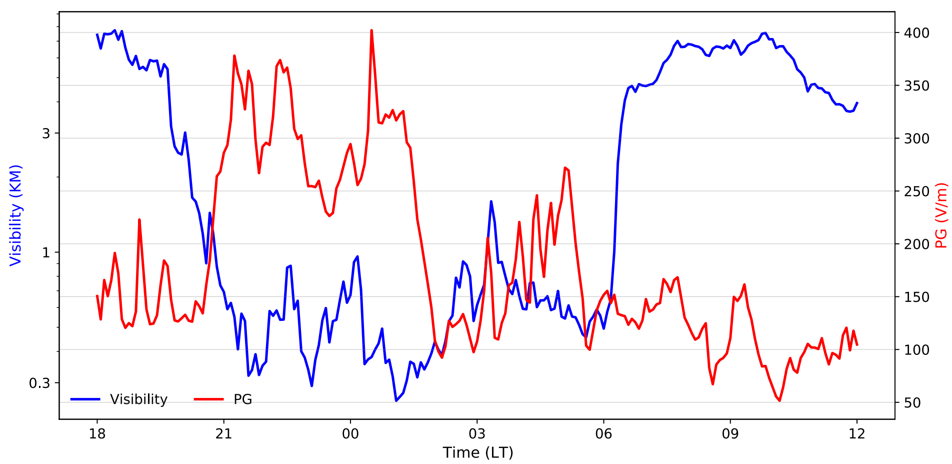

Figure 6. Timeseries of PG and Visibility obtained at RUAO. The period used ranged from 18 UK LT December 31st, 2020 till 12 UK LT January 01st, 2021. The PG and visibility data were at 5-minute time resolution. The visibility data are presented on a logarithmic scale.

Figure 6 shows a sharp increase in PG from 120 to 400 V/m at 20:30 LT. At the same time, the visibility reduced rapidly from 7 km down to 250 m, signifying the presence of a dense fog event. The PG remains large and positive until 02 LT where it decreases (coinciding with an increase in visibility) but remains very variable. The small values of visibility (500 – 800 m) during the period from 02 – 06 LT indicate that fog is still present but is less dense than during the earlier part of the morning. After 06 LT, the visibility increases rapidly (from 700 m up to 5 km), and the PG returns to more fair weather values, indicating fog dissipation. The increase in PG during the fog formation stage shown here is typical of what is expected from the theory of a conductivity decrease in fog due to ion-aerosol attachment (e.g., Harrison, 2012), and reported by others in the literature (e.g., Anisimov et al., 2005; Bennett and Harrison, 2009). This contrasts with the negative PG values shown in UAE fogs in Section 3.

To investigate the anomalous negative PG values observed in the UAE, it is useful to compare statistical information from UAE fog events with UK events. Table 1 shows a statistical summary of median PG, PG variability, maximum PG and minimum visibility during fog and non-fog (defined as visibility ≥10 km) for a continuous 10-day period in the UAE and UK. The timeframe selected for this analysis was from 21:00 to 09:00 LT in the UAE and from 18:00 to 09:00 LT in the UK, chosen to coincide with periods when fog is most likely to occur and to minimise the effects of other weather conditions. It should be noted that there are only 5 fog events (selected during the winter period) analysed for each site here. This small sample of fog events is not intended to give a full representation of fog characteristics for the two sites but is included here merely to provide an example of the general differences in PG behaviour between the two sites. The analyses for the fog events were computed only during periods where the visibility fell below 1 km. In contrast, for the non-fog events, these quantities were calculated using visibility values ≥10 km. The variability of PG is estimated as the interquartile range divided by 1.349 (i.e., adjusted to be equivalent to the standard deviation for a normally distributed dataset).
Table 1 shows that in non-fog conditions the median PG is similar between the two sites (111 V/m in the UAE, and 104 V/m in the UK). This becomes very different in fog, with a negative median PG of -7 V/m in the UAE, but large and positive median PG of 235 V/m in the UK. The maximum PG values in the 5 fog cases are comparable for both sites (336 V/m in UAE and 402 V/m in UK), but, as is shown in Figure 5, in fog PG values can be much larger (up to 1400 V/m) in the UAE. Variability in PG was larger in the UAE for both non-fog (61 V/m compared to 26 V/m in UK) and fog cases (160 V/m compared to 102 V/m in UK) as would be expected from the increased aerosol loading in the UAE. The minimum visibility during the 5 UAE fog events was also found to be lower (40 m) than in the UK (250 m), signifying more dense fog events in the UAE.

Region	**Fog**				**Non-Fog**				**Number of Fog Cases**
	Median PG (V/m)	**PG Variability (V/m)**	**Max PG (V/m)**	**Min Visibility (km)**	**Median PG (V/m)**	**PG Variability (V/m)**	**Max PG (V/m)**	**Min Visibility (km)**	
UAE	-7	160	336	0.04	111	61	460	10.02	5
UK	235	102	402	0.25	104	26	195	10.03	5

Table 1. Summary of the statistical comparison performed during fog and non-fog conditions in the UAE (Sanad Academy) and the UK (RUAO). The observation period used for the UAE was from March 30th, 2021 till April 09th,2021, while for the UK was from December 30th, 2020 till January 10th, 2021. The selected timings for the UAE were between 21 to 09 UAE LT only, while for the UK were between 18 to 09 UK LT only. Visibility range of ≥10 km was used for non-fog conditions. PG variability is expressed in terms of interquartile range (IQR) divided by 1.349.

4.2 PG and Visibility relationship

To investigate the anomalous negative PG values observed in the UAE further, it is instructive to examine the relationship between the PG and visibility for both the UAE and Reading sites during fog events, as illustrated in Figure 7. This analysis aims to test theoretical predictions, as reported by Harrison (2012), which suggest a predictable relationship between the PG and the visibility due to the close association between PG and air conductivity. Figure 7 shows PG and visibility data for the 5 fog events in Table 1, for (a) the UAE (Sanad Academy), and (b) Reading, UK. In fog events observed in the UK (Figure 7 (b)), a clear relationship is demonstrated between the PG and the visibility. PG is largest for the lowest visibility values and decreases towards more fair weather values as the visibility increases. At higher visibilities (> 1 km), the PG ceases to change with increasing visibility and instead becomes steady, reaching an asymptotic behaviour. These findings align with the previous observations of PG behaviour during fog in the UK, as reported in Harrison (2012) and Harrison and Nicoll (2018).

Conversely, the relationship observed between PG and visibility during fog events in the UAE (Figure 7 (a)) is much less obvious, with no clear relationship observed between the two. Also, as noted previously, many of the PG values are negative. These findings suggest that the PG changes observed during many fog events in the UAE are not dominated by conductivity changes (which are indicative of visibility variations). It is possible that charging of the fog droplets (which is discussed more fully in section 5, and not included in the theoretical relationship derived in Harrison (2012)) modifies the PG/visibility relationship beyond what is expected from the neutral fog droplet case, but further measurements are needed to confirm this.

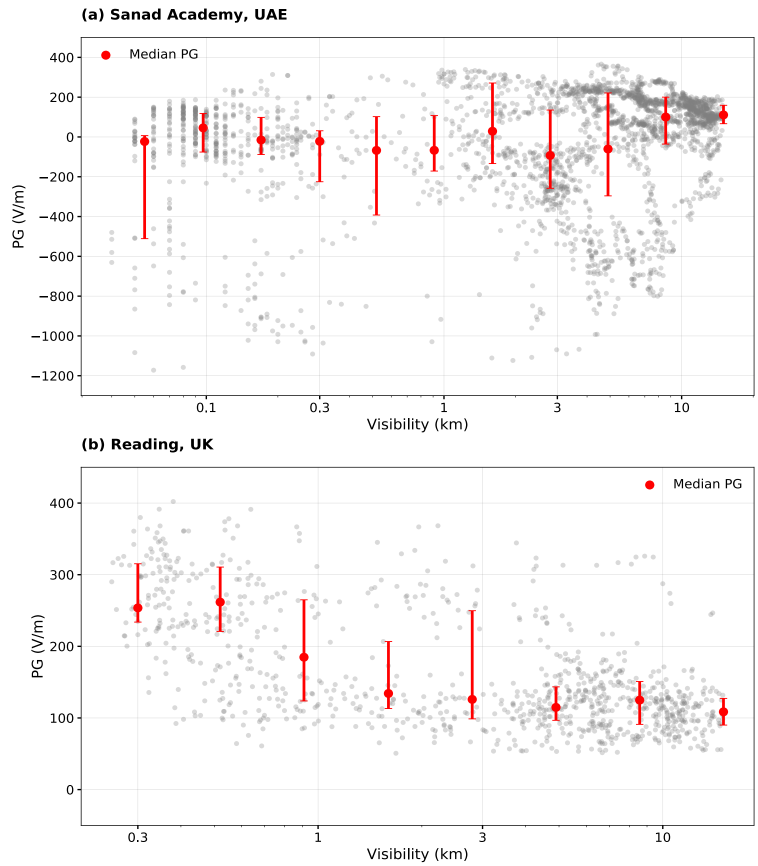

Figure 7. Relationship between PG and visibility during fog at (a) Sanad Academy and (b) Reading University Atmospheric Observatory (RUAO). Red dot represents the median PG values including interquartile ranges binned based on visibility at Sanad Academy (11 bins from 0.055 to 15 km) and RUAO (8 bins from 0.30 to 15 km). Data from Sanad Academy was from March 30th, 2021 to April 09th, 2021 with time selected between 21 to 09 UAE LT only, while for RUAO data was from December 30th, 2020 till January 10th, 2021 with time selected between 18 to 09 UK LT only. During the selected periods, 5 fog cases were observed at each site. The visibility data are presented on a logarithmic scale.

5. Discussion

Based on the analysis presented in this study, it is evident that the electrical characteristics of fog in the UAE differ from those typically observed at some midlatitude sites such as the UK. The observed transition of the PG behaviour to negative values during the fog events in the UAE contradicts the findings of many previous studies (e.g., Nizamuddin and Ramanadham, 1983; Anisimov et al., 2005; Bennett and Harrison, 2007; Bennett and Harrison, 2008; Harrison, 2012; Harrison and Nicoll, 2018; Yair and Yaniv, 2023). These studies have reported an increase in the PG, which is likely attributed to the removal of ions by fog droplets, resulting in a decrease in air conductivity, through Ohm's law (equation 1). Figure 4 demonstrate that in fog events at Sanad, the PG increases as expected during the initial fog formation stage, but then decreases and becomes negative. In order for the PG to become negative during fog it is likely that an additional charge separation/generation mechanism (either natural or artificially) must be present. Previous research by Chalmers and Little (1947) and Chalmers (1952) measured negative PG values during fog, which they attributed to generation of negatively charged ions from power cables. This negative charge is likely to be transferred to the fog droplets, potentially leading to a reversal in polarity of the PG. Although the measurement mast at Sanad Academy is approximately 400 m from any buildings, with no known sources of artificial charge generation, it is possible (though unlikely) that nearby factories or construction work could be responsible for the negative PG values.

Another possible explanation is related to the observation that fogs at Sanad Academy are noticeably wet, which we refer to here as “drizzling fog”. Often the desert surface during such fog events is extremely damp, with visible droplets on equipment. Evidence of large fog droplet diameters observed in the UAE is discussed in the findings of Weston et al. (2021), where the peak of the droplet size distribution has been measured to be 25 μm during fog in the UAE, compared to peaks below 10 μm in some midlatitude sites. It is possible that very large “drizzling” fog droplets may splash and release charged ions on impact with the surface (and the surface of the field mill), potentially leading to negative values of PG, as is observed during rain events (e.g., Simpson, 1909; Levin and Hobs, 1971; Kamra et al., 2015), but the rain rates required for splashing to occur are likely to be larger than would occur during “drizzling fog” conditions.

An alternative, more likely, hypothesis is related to the deposition of droplets, which is a common phenomenon during radiation fog (Duynkerke, 1991). In theory, within a stable cloud layer, positive charges are likely to accumulate on droplets at the cloud top due to the vertical current from the global electric circuit as it flows through the vertical conductivity gradient at the boundary between the clear air and droplet-laden air (Harrison et al., 2020; Nicoll and Harrison 2010; Zhou and Tinsley 2012). We hypothesize that the conductivity change at the upper boundary of a fog layer is similar to that in a stratiform layer, and is likely to produce positive charge as suggested by theory. Although the authors are not aware of any charge measurements of this phenomena in fog, it is well documented in the stratiform cloud case (Nicoll and Harrison, 2016), where it has been observed that the charge at the cloud top is often larger than at cloud base, due to strong temperature inversions at cloud top, which provide a “sharper” transition between clear and cloudy air. Vertical profiles of microphysical fog droplet properties by Egli et al., (2015) demonstrate that fog tops are often associated with strong temperature inversions, and sharp changes in fog droplet concentrations (as is the case for stratiform clouds), therefore it is reasonable to suggest that fog tops will be similarly charged to stratiform clouds. Once the droplets become large enough, deposition of the fog droplets will transport the positive charge (which exists on the droplets) downwards towards the surface, which is likely to modify the PG, causing it to decrease and potentially become negative. This is expected to occur particularly during the latter stages of fog events where the droplet size distribution has fully evolved (Katata 2014; Lovett 1984). The formation of larger drops and their subsequent deposition is a characteristic of the dissolving of long-lived fog.

The observation that the negative PG values only occur during winter fogs (when the fogs are denser and long lived), supports the possibility that these fogs have the potential to contain larger droplets than fogs during the summer months, and also that the conductivity gradient between clear and foggy air at fog top is larger (which, theoretically, leads to more positive charge), but more research is required to fully explain the occurrence of negative PG values during fog in the UAE.

The large positive values of PG observed in the UAE summer months (up to 1400 V/m) are generally larger than those reported in the literature (Nizamuddin and Ramanadham, 1983; Anisimov et al., 2005; Bennett and Harrison, 2007; Bennett and Harrison, 2009; Harrison and Nicoll, 2018; Yair and Yaniv, 2023), which may be related to differences in the fog droplet number concentration and size distributions between the various sites. The high aerosol content in the UAE (from lofted sand and industrial pollution) may also influence the fog droplet properties, as well as the background conductivity, which has likely implications for the PG (e.g., Zheng, 2013; Nicoll et al., 2020), which also needs further investigation.

6. Conclusions

Forecasting fog onset and dissipation remains a challenging task despite the improvements in numerical weather prediction (NWP) models. The need of improving the forecast accuracy is required to mitigate major losses caused by fog. This study aims to investigate whether electrical properties of the atmosphere may serve as a useful tool to aid fog forecasting, by understanding the electrical characteristics of fog in the UAE, which experiences regular fog events. These surface electrical measurements of fog are the first to be conducted in the UAE, and hence, are compared to previous studies made in the UK.

This study established that the electrical behavior of fog in the UAE is different to that in the UK, especially during winter fog. Unlike in previous studies (Nizamuddin and Ramanadham, 1983; Anisimov et al., 2005; Bennett and Harrison, 2007; Bennett and Harrison, 2008; Harrison, 2012; Harrison and Nicoll, 2018; Yair and Yaniv, 2023), the PG in the UAE experienced opposite polarity during the presence of fog. 93% (25 out of 27) of fog cases included periods of negative PG, with the median minimum PG during fog being -397 V/m. Analysis of the relationship between PG and visibility in the UAE during fog conditions showed no clear correlation between the two, suggesting that PG changes in fog in the UAE are not dominated by conductivity changes.

The transition of PG to negative values during fog is considered an unusual phenomenon, which we hypothesize to occur due to the deposition of positively charged fog droplets. The positive charge is hypothesized to exist at the top of the fog layer, from vertical current flow in the Global Electric Circuit. During the deposition process, positive charge is suggested to be transported downwards toward the surface, modifying the surface PG. This is likely to be particularly active during the latter stages of the fog when the droplet size distribution has fully evolved. The negative PG did not occur during summer time fog events, where the PG was observed to increase solely as a result of the formation of fog over a brief duration. Hence, the droplets do not have enough time to grow in size. Currently, our research focuses on analysing droplet size distribution using an optical sensor to investigate the growth of droplet size during fog events in the UAE to investigate this hypothesis further.

Furthermore, the quantified variability of the PG during foggy and non-foggy conditions were used to compare between the UAE and the UK. The results showed that the PG exhibited significantly higher variability in the UAE during foggy conditions, with a measured variability of 160 V/m compared to 102 V/m in the UK. In addition, the median PG during fog in the UAE was very different from that observed in the UK, with median of -7 V/m compared to 235 V/m in the UK. This may occur due to differences in turbulent characteristics of the fog, differences in droplet size/number/ charge properties, or variations in the fog droplet charge between the two environments.

It can be concluded that fog occurrences during the winter season in the UAE consistently exhibit different PG behaviour to those generally reported in the literature, making it an unusual phenomenon that diverges from fog events observed in clean air environments.

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Data Availability

Potential gradient and visibility data are openly available and can be accessed online from the University of Reading Data Repository at https://doi.org/10.17864/1947.000501. Wind speed, wind direction, and EUMETSAT satellite data can be requested from the National Center of Meteorology, UAE.

References

Agarwal, A., Bhattacharya, S., Chaudhari, S., 2020. Electric Field Mill, an Effective Methodology to Measure the Localized Lower Atmospheric Electric Field. Mat. Proc. 29. 440 – 447. DOI: 10.1016/j.matpr.2020.07.297.

Ali, O.W.B., Al-Harthei, H., Garib, A., 2013. Real-Time Fog Warning System for the Abu Dhabi Emirate (UAE). J. Traff. Log. Eng. 1. 213 – 217. DOI: 10.12720/jtle.1.2.213-217.

Anisimov, S.V., Mareev, E.A., Shikhova, N.M., Sorokin, A.E., Dmitriev, E.M., 2005. On the electro-dynamical characteristics of fog. J. Atmos. Res. 76. 16 – 28. DOI: 10.1016/j.atmosres.2004.11.026.

Bateman, M.G., Stewart, M.F., Podgorny, S.J., Christian, H.J., Mach, D.M., Blakeslee, R.J., Bailey, J.C., Daskar, D., 2007. A Low-Noise, Microprocessor- Controlled, Internally Digitizing Rotating-Vane Electric Field Mill for Airborne Platforms. Amer. Meteor. Soc. 24. 1245 – 1255. DOI: 10.1175/JTECH2039.1.

Bennett, A.J., Harrison, R.G., 2007. Atmospheric electricity in different weather conditions. Roy. Meteor. Soc. 62. 277 – 283. DOI: 10.1002/wea.97.

Bennett, A.J., Harrison, R.G., 2008. Variability in surface atmospheric electric field measurements. J. Phys.: Conf. Ser. 142. DOI: 10.1088/1742-6596/142/1/012046.

Bennett, A.J., Harrison, R.G., 2009. Evidence for global circuit current flow through water droplet layer. J. Atmos. Solar-Terr. Phys. 71. 1219 – 1221. DOI: 10.1016/j.jastp.2009.04.011.

Chalmers, J.A., Little, E.W.R.,1947. Currents of atmospheric electricity. Terr. Magn. Atmos. Electr. 52. 239 – 260. DOI: 10.1029/TE052i002p00239.

Chalmers, J.A., 1952. Negative electric fields in mist and fog. J. Atmos. Terr. Phys. 2. 155 – 159. DOI: 10.1016/0021-9169(52)90060-3.

De Villiers, M.P., van Heerden, J., 2007. Fog at Abu Dhabi International Airport. Roy. Meteor. Soc. 62. 209 – 214. DOI: 10.1002/wea.45.

Dolezalek, H., 1973. On the Electro-atmospheric Fog Effect. Pure Applied Geophys. 105. 907 – 909. DOI: 10.1007.BF00875840.

Duynkerke, P.G., 1991: Radiation Fog: A Comparison of Model Simulation with Detailed Observations. *Mon. Wea. Rev.* **119**. 324 – 341. DOI: 10.1175/1520-0493(1991)119<0324:RFACOM>2.0.CO;2.

Eager, E.R., Raman, S., Wootten, A., Westphal, D.L., Reid, J.S., Al Mandoos, A., 2008. A climatological study of the sea and land breezes in the Arabian Gulf region. J. Geophys. Res. 113. 1 – 12. DOI: 10.1029/2007JD009710.

Egli, S., Maier, F., Bendix, J., Thies, B., 2015. Vertical distribution of microphysical properties in radiation fogs – A case study. J. Atmos. Res. 151. 130 – 145. DOI: 10.1016/j.atmosres.2014.05.027.

Harrison, R.G., 2012. Aerosol-induced correlation between visibility and atmospheric electricity. J. Aero. Sci. 52. 121 – 126. DOI: 10.1016/j.jaerosci.2012.04.011.

Harrison, R.G., 2011. Fair weather atmospheric electricity. J. Phys.: Conf. Ser. 301. DOI:10.1088/1742-6596/301/1/012001.

Harrison, R.G., Marlton, G.J., Ambaum, M.H.P., Nicoll, K.A., 2022. Modifying natural droplet systems by charge injection. Phys. Rev. Res. 4. 1 – 6. DOI: 10.1103/PhysRevResearch.4.L022050.

Harrison, R.G., Nicoll, K.A., 2018. Fair weather criteria for atmospheric electricity measurements. J. Atmos. Solar-Terr. Phys. 179. 239 – 250. DOI: 10.1016/j.jastp.2018.07.008.

Harrison, R.G., Ambaum, M.H.P., 2008. Enhancement of cloud formation by droplet charging. Proc. Roy. Soc. 464. 2561 – 2573. DOI: 10.1098/rspa.2008.0009.

Harrison, R.G., Nicoll, K.A., Mareev, E., Slyunyaev, N., Rycroft, M.J., 2020. Extensive layer clouds in the global electric circuit: their effects on vertical charge distribution and storage. Proc. Roy. Soc. 476. 1471 – 2946. DOI: 10.1098/rspa. 2019.0758.

Harrison, R.G., 2015. Meteorological Measurements and Instrumentation. John Wiley & Sons, Ltd. 257 pp.

Hoppel, W.A., Anderson, R.V., Willett, J.C., 1986. Atmospheric Electricity in the Planetary Boundary Layer, The Earth's Electrical Environment. National Academy Press. 149 – 165.

Izett, J.G., van de Wiel, B.J.H., Baas, P., Bosveld, F.C., 2018. Understanding and Reducing False Alarms in Observational Fog Prediction. Boundary-Lay. Meteor. 169. 347 – 372. DOI: 10.1007/s10546-018-0374-2.

Kamra, A.K., Gautam, A.S., Siingh, D., 2015. Charged nanoparticles produced by splashing of raindrops. J. Geophy. Res. 120. 6669 – 6681. DOI: 10.1002/2015JD023320.

Katata, G., 2014. Fogwater deposition modeling for terrestrial ecosystem: A review of developments and measurements. J. Geophy. Res. Atmos. 119. 8137 – 8159. DOI:10.1002/2014JD021669.

Levin, Z., Hobbs, P.V., 1971. Splashing of water drops on solid and wetted surfaces: hydrodynamics and charge separation. Philosophical Transactions of the Royal Society of London. 269. 555 – 585. DOI: 10.1098/rsta.1971.0052.

Li, D., Li, C., Li, J., Yang, W., Xiao, M., Zhang, M., Yang, Y., Yu, K., 2022. Efficient direction- independent fog harvesting using a corona discharge device with a multi-electrode structure. Plasma Sci. Technol. 24. 1 – 10. DOI: 10.1088/2058-6272/ac6be4.

Lovett, G.M., 1984. Rates and mechanisms of cloud water deposition to a subalpine balsam fir forest. Atmos. Environ. 18. 361 – 371. DOI: 10.1016/0004-6981(84)90110-0.

Miller, S.T.K., Keim, B.D., Talbot, R.W., Mao, H., 2003. Sea Breeze: Structure, Forecasting, and Impacts. Rev. Geophys. 41. DOI: 10.1029/2003RG000124.

Mohan, T.S., Temimi, M., Ajayamohan, R.S., Nelli, N.R., Fonseca, R., Weston, M., Valappil, V., 2020. On the Investigation of the Typology of Fog Events in an Arid Environment and the Link with Climate Patterns. Amer. Meteor. Soc. 148. 3181 – 3202. DOI: 10.1175/MWR-D-20-0073.1.

Nelli, N., Fissehaye, S., Francis, D., Fonseca, R., Temimi, M., Weston, M., Abida, R., Nesterov, O., 2021. Characteristics of Atmospheric Aerosols over the UAE Inferred From CALIPSO and Sun Photometer Aerosol Optical Depth. Earth and Space Sci. 8. 1 – 18. DOI: 10.1029/2020EA001360.

Nicoll, K.A., Harrison, R.G., Marlton, G., Airey, M., 2020. Consistent dust electrification from Arabian Gulf sea breezes. Environ. Res. Lett. 15. DOI: 10.1088/1748-9326/ab9e20.

Nicoll, K.A., Harrison, R.G., 2010. Experimental determination of layer cloud edge charging from cosmic ray ionisation. Geophys. Res. Lett. 37. DOI: 10.1029/2010GL043605.

Nicoll, K.A., 2012. Measurements of Atmospheric Electricity Aloft. Surv. Geophys. 33. 991 – 1057. DOI: 10.1007/s10712-012-9188-9.

Nicoll, K.A., Harrison, R.G., 2016. Stratiform cloud electrification comparison of theory with multiple in-cloud measurements. Quart. J. Roy. Meteor. Soc. 142(700). 2679 – 2691. DOI: 10.1002/qj.2858.

Nicoll, K.A., Readle, A., Al Kamali, A., Harrison, R.G., 2022. Surface atmospheric electric field variability at a desert site. J. Atmos. Solar-Terr. Phys. 241. 1 – 11. DOI: 10.1016/j.jastp.2022.105977.

Nizamuddin, S., Ramanadham, R.,1983. The Electric Potential Gradient in Mist, Haze, and Fog. PAGEOPH. 121. 353 – 359. DOI: 10.1007/BF02590144.

Roman-Cascon, C., Steeneveld, G.J., Yague, C., Sastre, M., Arrillaga, J.A., Maqueda, G., 2016. Forecasting radiation fog at climatologically contrasting sites: evaluation of statistical methods and WRF. Quart. J. Roy. Meteor. Soc. 142. 1048 – 1063. DOI: 10.1002/qj.2708.
Rycroft, M.J., S. Israelsson and C. Price, 2000: The global atmospheric electric circuit, solar activity and climate change. J. Atmos. Solar-Terr. Phys.62. 1563 – 1576. DOI: 10.1016/s1364-6826(00)00112-7.

Serbu, G.P., Trent, E.M., 1958. A study of the use of atmospheric -electric measurements in fog forecasting. Eos Trans. Amer. Geophy. Union. 39. 1034 – 1042. DOI: 10.1029/TR039i006p01034.

Simpson, G.C., 1909. XV. On the electricity of rain and its origin in thunderstorms. Philosophical Transactions of the Royal Society of London. 209. 379 – 413. DOI: 10.1098/rsta.1909.0015.

Tag, P.M., 1976. A Numerical Simulation of Warm Fog Dissipation by Electrically Enhanced Coalescence: Part I. An Applied Electric Field. J. Applied Meteor. Climatology. 15. 282 – 291. DOI: 10.1175/1520-0450(1976)015<0282:ANSOWF>2.0.CO;2.

Tai, H., Zhuang, Z., Jiang, L., Sun, D., 2017. Visibility Measurement in an Atmospheric Environment Simulation Chamber. Current Optics and Photonics. 1. 186 – 195. DOI: 10.3807/COPP.2017.1.3.186.

Tardif, R., Rasmussen, R.M., 2007. Event-Based Climatology and Typology of Fog in the New York City Region. J. Applied Meteor. Climatology. 46. 1141 – 1168. DOI: 10.1175/JAM2516.1.

Weston M., Temimi, M., Burger, R., Piketh, S., 2021. A Fog Climatology at Abu Dhabi International Airport. J. Applied Meteor. Climatology. 60. 223 – 236. DOI: 10.1175/JAMC-D-20-0168.1.

Wilson, C.T.R., 1921. III. Investigations on lightning discharges and on the electric field of thunderstorms. Philosophical Transactions of the Royal Society of London. 221. 73 – 115. DOI: 10.1098/rsta.1921.0003.

World Meteorological Organization, 2012. Guide to Meteorological Instruments and Methods of Observations. Accessed 16 August 2022, from: https://library.wmo.int/doc_num.php?explnum_id=10616

Yair, Y., Yaniv, R., 2023. The Effects of Fog on the Atmospheric Electrical Field Close to the Surface. J. Atmos. 14. 1 – 12. DOI: 10.3390/atmos14030549.

Zheng, M., Li, J., Li, C., He, F., Li, D., Yu, K., Pan, Y., 2023. Investigation of the effects of parallel electric field on fog dissipation. J. Phys. D: Applied Phys. 56. 1 – 10. DOI: 10.1088/1361-6463/acd85c.

Zheng, X.J., 2013. Electrification of wind-blown sand: Recent advances and key issues. Eur. Phys. J. E. 36. 1 – 15. DOI: 10.1140/epje/i2013-13138-4.

Zhou, L., Tinsley, B.A., 2012. Time dependent charging of layer clouds in the global electric circuit. Advances Space Res. 50. 828 – 842. DOI: 10.1016/j.asr.2011.12.018.

Appendix A

A.1 Instrumentation

A.1.1 Campbell CS110: Electric Field Meter

Being robust to all meteorological conditions makes the electric field mill as one of the reliable ways for continuous measurements of atmospheric electric fields (Agarwal et al., 2020; Bennett and Harrison, 2007). The electric field mill consists of a sensing electrode, which is shielded and exposed via a mechanical shutter (Bateman et al., 2007; Nicoll, 2012). As the electrode vane rotate, they become shielded and exposed with the aid of the motor, which in turn causes charge to be induced as it gets exposed (Agarwal et al., 2020; Bennett and Harrison, 2007). This charge is proportional to the electric field (Harrison, 2015).

In this research, A Campbell CS110 electric field meter was used to measure the atmospheric electric fields (see Figure 2(b)). In terms of measurements ranges, the electric field meter was mounted at 3m above ground and set to measure the electric fields at $\pm$ 20 k V/m. In terms of datalogging, the electric field data were logged each 1-second, which was then averaged to 1-minute mean values to conduct this study.

A.1.2 Biral SWS-100: Visibility Sensor

One of the commonly performed meteorological observation is visibility (Tai et al., 2017). Visibility sensors are considered the main tool in detecting fog. In this study, Biral SWS-100 was used to estimate the optical range in the site (see Figure 2 (b)). The sensor uses the forward scattering method to measure the visibility (Izett et al., 2018). This works by sending out a beam of light from the transmitter, while the receiver measures the light scattered forward by the particles in the air (WMO, 2012). The visual range decreases as the particles in the air increase, which cause more scattering of light (Harrison, 2015).

In this study, the sensor was configured to have a maximum visual range of 50 km and the visibility data were logged at a time resolution of 1 minute. In addition, the SWS-100 also includes a present weather sensor, which can help in identifying the presence of fog. One of the issues encountered was the contamination of the sensor's windows, which was mainly caused due to dust and sand surrounding the field site.

A.1.3 Standard Meteorological Sensor

To verify the presence of fog and other weather conditions, standard meteorological data were obtained from an automatic weather station in Al Marmoom, Dubai. As discussed, Al Marmoom AWS is located about 9 km away from the observation site. This was chosen mainly because no standard meteorological measurements were available in the observation site until January 2022. In addition, the station was the closest available to Sanad Academy, in which the results were expected to link.

The weather parameters focused on were the wind speed (in m/s) and direction, the RH, and the dry bulb temperature (in °C). All these parameters were useful in confirming the present weather in the field site. For example, the wind speed and direction were used to verify some of the sudden changes in the PG data. In addition, the dry bulb temperature and the RH were used to calculate the dew point temperature (in °C), which was also useful to confirm the presence of fog. Other variables such as rainfall amount (in mm), air pressure (in hPa) and solar radiation (in W/m^2) were used occasionally for extra support. The standard meteorological data at Al Marmoom AWS were logged at 15-minute time resolution.

A.2 Diurnal variation during fair weather conditions

To compare the electrical properties during disturbed weather conditions to those observed during fair weather conditions, the average typical diurnal variation in PG under fair weather conditions was derived using data collected throughout the year 2021. The criteria used to identify fair weather conditions included wind speed less than 4 m/s, visibility greater than 20 km, and present weather code equals to 0 (i.e., no significant weather observed). A high visibility threshold was used to minimise the influence of aerosol particles, which can affect the PG measurements. Figure A1 demonstrates the hourly mean diurnal variation in PG and visibility during fair weather conditions. The analysis reveals that typical PG values during such conditions are positive with median values ranging between 90 to 250 V/m, which aligns with the previous findings (i.e., Bennett and Harrison, 2007). The peak in PG between 16-17LT is likely to be associated with the arrival of the sea breeze front (e.g., as observed for other UAE sites (Nicoll et al, 2022)). When compared to the foggy events, the PG during fair weather conditions demonstrates lower variability with fewer sharp changes, and exclusively positive PG values.

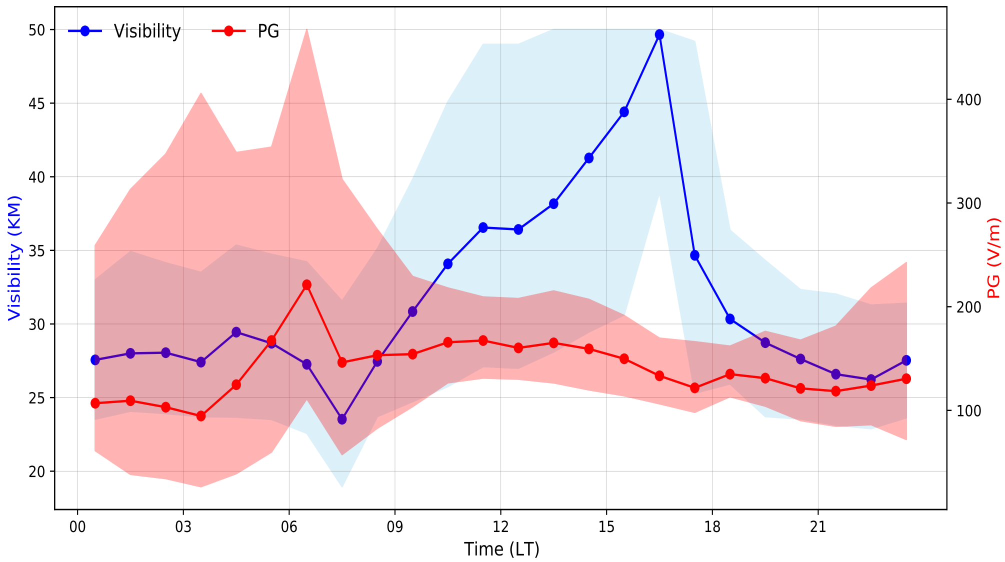

Figure A1. Diurnal variation in PG and Visibility along with the interquartile ranges under fair weather conditions at Sanad Academy. The displayed data points are hourly medians using 1-minute values throughout all 2021 data. The criteria used to identify fair weather conditions included wind speed less than 4 m/s, visibility greater than 20 km and present weather code equals to 0 (i.e., no significant weather).