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Consistent dust electrification from Arabian Gulf sea breezes

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Environmental Research Letters

LETTER

Consistent dust electrification from Arabian Gulf sea breezes

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Abstract

The Arabian Gulf region experiences regular thermally driven sea breeze circulations which occur all year round, penetrating hundreds of kilometres inland. As a sea breeze front moves inland, substantial electric fields are generated by separation of charged desert dust. In the first surface electric field measurements made in the United Arab Emirates (UAE), consistent and repeatable substantial electric field changes with magnitudes up to 7 kV m^{-1} have been detected at Al Ain (170 km from the western coast), during 80 separate sea breeze events in 2018. Every sea breeze frontal passage shows the same characteristic signature of a transient maximum peak in electric field lasting tens of minutes. Electric field changes during these events were always negative (i.e. enhancing the existing negative 'fair weather' electric field), in contrast to many other reported observations in dust storms in which conditions were less repeatable. The regular and substantial dust electrification found demonstrates that accurate representation of dust in climate and weather models requires electrical effects to be addressed, both in the generation process, and by considering aggregates in radiative transfer calculations as electrically aligned rather than randomly ordered. Furthermore, satellite aerosol retrievals are affected by the changed attenuation of electromagnetic radiation when dust particles are charged, for which corrections may be needed.

1. Introduction

Electrification of dust in the atmosphere occurs readily, with its effects made apparent in sparks from barbed wire fences during the 1930s 'Dust Bowl' in the US [1], and helicopter blades glowing from corona discharge in dusty environments [2]. Dust electrification can result from contact charging/triboelectrification [3, 4], during dust generation or its atmospheric transport [5, 6]. Charging of dust particles, and separation of the charge by mechanical processes yields large electric fields (E-fields), which can be several orders of magnitude larger (up to tens of kV m^{-1}) than those more typical of fair weather conditions in non-desert regions. These fields are substantial enough to alter the properties of insulators on transmission lines in desert areas, reducing the flashover voltage [7]. Dust electrification also has applications to climate studies, through electrical influences on the behaviour of dust, and its radiative behaviour in particular [8]. Satellite remote sensing of dust is based on measurements of electromagnetic wave propagation which are attenuated by large electric fields [9], thereby the accuracy of dust measurements can be affected by electric fields arising from charge separation in dusty environments. Large E-fields associated with charge separation in dust layers are also expected to alter the orientation of dust particles, changing the effective optical depth of dust layers [10], existing calculations for which assume randomly oriented particles. Further consequences associated with dust electrification are that the dust lofting process itself can be altered when the E-field intensity exceeds a threshold value (thought theoretically to be 150 kV m^{-1} in the few cm closest to the surface) [11]. This results in a sudden increase in the concentration of lofted particles at a given wind speed [12], unaccounted for in dust source modelling. Finally, electrification of dust particles has also been suggested to alter the transport of the dust particles by increasing the time spent aloft through interaction with the background E-field [5, 8]. Due to the developing knowledge concerning dust charging processes in the real atmosphere, no

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Figure 1. (a) Downward-facing electric field meter beneath a visibility sensor on a mast installed at Al Ain airport, United Arab Emirates. (b) Map of the UAE, showing the location of the Al Ain measurement site as the red circle. The red arrow denotes the typical direction of the source of the sea breeze. Map data © 2020 Google; imagery © 2020 TerraMetrics.

attempts have yet been made to incorporate the role of dust charging into satellite retrievals of dust, or in modelling the dust source regions which are key to accurate predictions from weather and global climate models.

Dust particles become charged through a variety of mechanisms, with the most dominant being contact electrification and triboelectrification [13]. Dust is lifted from the surface by the wind, enhanced by saltation and resuspension [14]. Collisions between dust particles cause charge to be transferred between them, resulting in a net charge on the particles which is thought to depend on particle size [4] as well as particle composition [15]. Smaller particles (which are generally found to be negatively charged) are lofted highest into the atmosphere by convective processes, leaving the larger (and generally more positively charged) dust particles near the surface. Such charge separation leads to the generation of large electric fields, which have previously been observed to be dominantly upward directed (i.e. positive electric field) [3, 16, 17]. Although progress has been made in recent years in understanding the physical processes by which dust becomes electrified, many unanswered questions still remain, such as what is the role of dust particle composition in electrification processes, how does dust charging impact on transport of dust particles and satellite retrievals of dust, and what is the explanation for negative (downward-pointing) electric fields? The variable and sporadic nature of dust storms means that studying such processes is difficult, and that repeatable consistent circumstances have previously been rarely, if ever, obtained.

In this paper we present a unique new dataset of atmospheric electrical observations from a site in the United Arab Emirates (UAE) which experiences frequent and regular dust events of remarkable consistency, providing a new opportunity for studying dust charging processes in a repeatable natural system. These demonstrate that the sea breeze circulation in the Arabian Peninsula is an efficient charge generator for mineral dust and produces kV m^{-1} local electric fields on an almost daily basis, and further, that the electrification may be sufficient to influence the dust generation itself (as previously suggested by other researchers [12]). To the best of our knowledge, these measurements are the first atmospheric electrical measurements in the UAE to be reported in the literature.

2. Sea breeze circulation in the UAE

The meteorology of the Arabian Gulf region is characterised by regular sea and land breezes which are driven by diurnal heating and cooling of the land surface. The sea breeze is effectively an atmospheric density current, due to temperature differences between land and sea regions caused by differential solar heating [18, 19]. In the UAE, Eager *et al* [20] determined that a sea breeze forms on 77% of days throughout the year, with the summer months experiencing sea breezes on 90% of days. The arrival of the sea breeze front is characterised by a wind direction change to the NW (i.e. wind veers from 235° through north to 45°), associated with a wind speed increase of up to 5 m s^{-1}. Figure 1(b) shows a map of the UAE with the typical direction of the sea breeze (i.e. from the westerly coastline), indicated by the red arrow. The distance travelled by the sea breeze in the UAE can be substantial, reaching distances up to

300 km inland [20]; once the sea breeze sets in it can often continue until sunset.

The sea breeze front usually arrives at coastal regions around 10:00–11:00 LT (Local Time) (06:00–07:00 UTC), reaching the interior desert regions, such as Al Ain (which is 170 km from the nearest coast at Abu Dhabi), by 14:00–15:00 LT (10:00–11:00 UTC). Al Ain is one of the Emirates' largest cities (population 800 000). It has a hot desert climate with yearly rainfall averages of 96 mm, and temperatures ranging from 10 °C to 48 °C during the summer (JJA—June, July, August). The lack of rainfall [21], combined with local winds, means that dust lofting is a major source of aerosol contamination at Al Ain, and the UAE overall [22], as over 80% of the UAE is desert. Widespread local human activities including construction sites, cement plants, and water desalination plants also contribute substantially to aerosol loading at the site [23].

As the majority of land surface in the UAE is covered by sand, the sea breeze front lofts sand from the surface as it travels inland: Eck *et al* [24] noted a significant maximum in the Aerosol Optical Depth (AOD) at the SMART site in the UAE (located at Al Ain airport) around 12:00 UTC, associated with the arrival of the sea breeze front. Some electrification has been previously observed in sea breeze events in non-desert locations (not in the UAE), almost entirely associated with the charge released by liquid-related processes such as droplet splashing [25–27]. Because of the strong electrification known to be associated with dust and dust transport, this aspect of the desert sea breeze front is investigated further, at the Al Ain site.

3. Site instrumentation

Instrumentation was installed at Al Ain international airport (24°15′ N, 55°37′ E), UAE, operational from February 2018. A Campbell CS110 electric field mill, Biral SWS100 visibility sensor and Vaisala CL31 ceilometer were installed approximately 2 km from the airport's main runway, with the CL31 and SWS100 spaced about 300 m from each other. The field mill was mounted at 3 m, configured to measure E-fields in the range ±20 kV m^{-1}. Meteorological observations including air temperature, RH (Relative Humidity), wind speed, visibility and present weather (which is any detectable weather phenomena occurring at the time of the observation) were obtained from regular METAR (METeorological Aerodrome Reports) observed at the airport (approximately hourly). E-field data was logged at 1 Hz and averaged to 1 min mean values for the analysis described here. Visibility was logged at 1 min time resolution. The typical undisturbed E-field at Al Ain is between −100 V m^{-1} and −200 V m^{-1}, but there are few 24 h periods in which the E-field remains without significant variability. Frequent daytime convection under mostly clear skies gives rise to convection currents which generate substantial E-fields (of magnitude up to several thousand kV m^{-1}), therefore the conventional understanding of 'fair weather' in atmospheric electricity terms (such as described in [28]) does not readily apply at this side. Detailed characterisation of the E-field at Al Ain during fair weather conditions is beyond the scope of the current paper, in which the focus is on electrification associated with the migrating sea breeze front.

4. Characteristics of dust charging in sea breezes

4.1. Single event

Figure 2 shows an example of data from the measurement site at Al Ain during 3 February 2018 during a typical sea breeze event. From figure 2(a) the arrival of the sea breeze front is at ∼15:00 UTC, and characterised by a sudden reduction in visibility (from 50 km down to 20 km), and an abrupt change in E-field from −100 V m^{-1} to −900 V m^{-1}. The wind (in figure 2(b)) also shows an increase in speed (albeit over a much longer timescale than the visibility and E-field changes) from 1.5 to 4.5 m s^{-1} (maximising just after the front's arrival time), and the direction becomes consistently WNW (∼300°), characteristic of flow from the Abu Dhabi coastline. Ceilometer data shown in figure 2(c) also demonstrates the distinct increase in the backscatter at ∼15:00 UTC as the front arrives. It should be noted that the high levels of backscatter from 0:00–6:00 UTC are not related to a dust layer, but are a result of a stable nocturnal layer which forms overnight and traps aerosol particles and water vapour beneath it. This erodes rapidly after sunrise as vertical mixing sets in from convective processes.

The transient change in E-field as the front arrives demonstrates that the material transported arrives charged. The initial change in E-field (from −100 to −900 V m^{-1}) occurs within a very short time period of 6 min, and is followed by an exponential decay to a background value of about −100 V m^{-1}, which takes around 90 min. Although the sea breeze continues for several hours afterwards (demonstrated by the continued reduction in visibility, the sustained increase in backscatter, and the constant wind speed until 19:00), there are no further significant changes in E-field. This suggests that the dust charging is associated with only the initial sea breeze front transition, and not the sea breeze itself.

The vertical depth of the aerosol-loaded sea breeze front can be seen in the ceilometer backscatter image (figure 3(a)) and vertical profiles of ceilometer data in figure 3(b). Three profiles are shown in (b), representing before (14:40—black), during (15:00—grey) and after (15:20—red) the sea breeze front arrives. Before the arrival of the front the backscatter is approximately constant with height at around 1 × 10^{-6} m^{-1} sr^{-1} which increases to

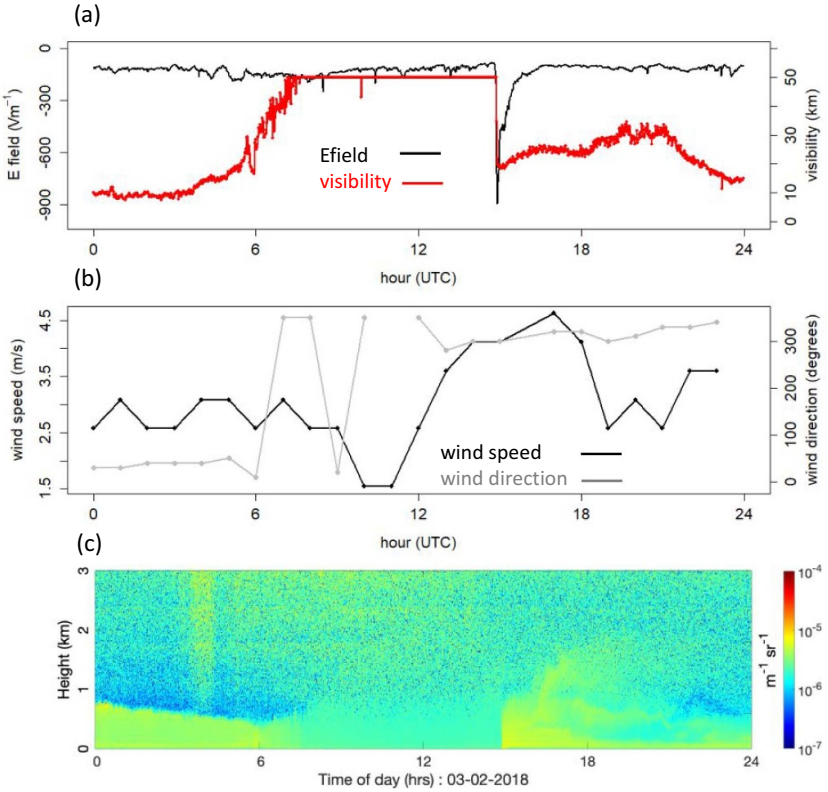

Figure 2. Time series from sea breeze event on 3 February 2018 at Al Ain. (a) Electric field (black), and visibility (red). (b) Wind speed (black) and wind direction (grey). (c) Backscatter data from the CL31 ceilometer. Electric field and visibility data are at 1 min resolution, and wind speed and direction at hourly resolution. CL31 ceilometer data is at 20 m height resolution, and 3 s time resolution. Times are in UTC, which is 4 h behind local time. The maximum visibility detectable by the visibility sensor is 50 km.

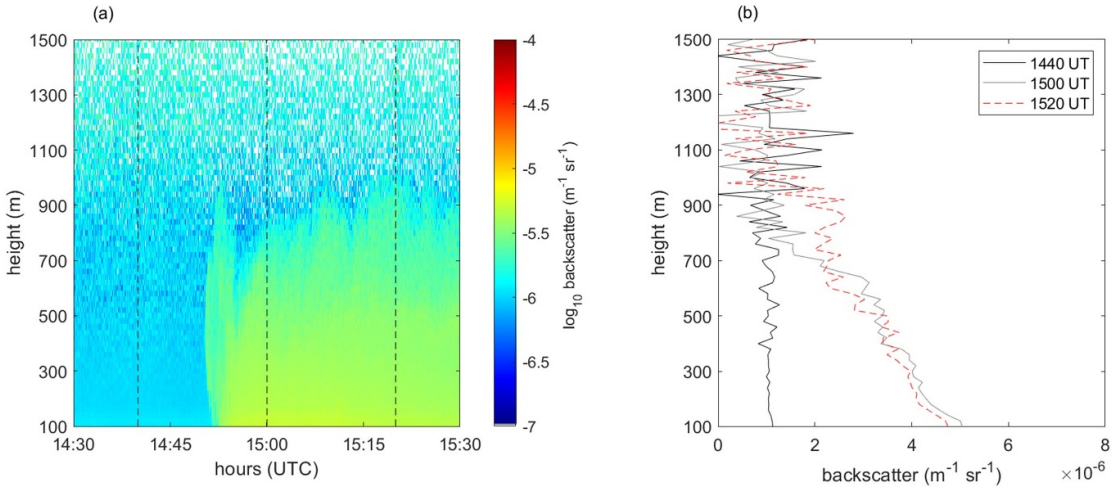

Figure 3. (a) Close up of backscatter data from the ceilometer around the time of the arrival of the sea breeze front event on 3 February 2018 at Al Ain. (b) Vertical profiles of backscatter at different times around the time of the front arrival (denoted by dashed vertical lines in (a)). Black = 14:40UTC (before the sea breeze arrival), thin grey = 15:00UTC (just after arrival of sea breeze front), dashed red = 15:20UTC (after passage of sea breeze front).

5×10^{-6} m^{-1} sr^{-1} at a height of 100 m when the front arrives. Although most of the frontal disturbance is within the lowest few hundred metres, the dust extends vertically to ~700 m. It should be noted that only ceilometer data above 100 m is considered further here due to known artefacts in the data below this altitude [29, 30].

4.2. Multiple sea breeze events

The data presented in figures 2 and 3 show a typical sea breeze front. During 2018, 80 such electrically active sea breeze events were detected at Al Ain, from a total of 199 days of available data. Further examples of detected sea breeze events are provided in the Supplementary Information (available at

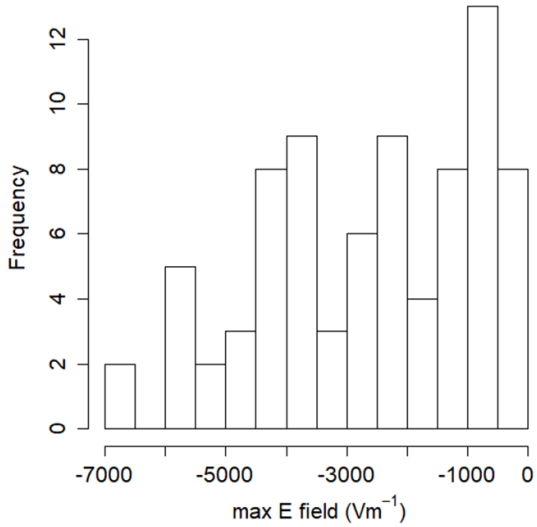

Figure 4. Histogram of the maximum E-field detected during 80 electrically active sea breeze front arrivals at Al Ain in 2018.

stacks.iop.org/ERL/15/084050/mmedia). In this analysis, electrically active sea breeze arrivals were detected entirely from transient E-field increases which occurred after 10:00 UTC at Al Ain (and identified by eye). The time of arrival of the electrically active sea breeze fronts was found to vary from 11:00 to 15:00 UTC. The 80 events represent electrical sea breeze occurrence on 40% of days during this period. [1] Figure 4 shows a histogram of the maximum of the E-field measured during each of the 80 detected electrically active sea breeze fronts at Al Ain. The smallest E-field was -192 V m^{-1} and the largest -6800 V m^{-1}. All of the 80 events registered a consistently negative E-field (i.e. increasing the fair weather field). This contrasts with most reported measurements of E-field in dusty environments (mostly dust storms), where the generated E-field is very often positive. Possible reasons for this are given in the Discussion section.

The simplicity of the electrical changes associated with the sea breeze front arrival (i.e. one single polarity peak in E-field), and the large number of events reported here, makes it possible to investigate the parameters likely to be controlling the E-field changes, in particular wind speed and dust concentration. Figure 5 summarises the relationships between E-field and wind speed, visibility and calculated dust concentration. The top row of plots ((a), (c) and (e)) shows a single value of the maximum in E-field as the sea breeze front passes for each of the 80 events. The bottom row shows the median of the maximum E-field values when the data are binned according to wind speed, visibility and dust concentration ((b), (d) and (f) respectively). It is well understood that the process of dust uplift depends strongly on the wind speed [31] and that there is a threshold wind speed above which dust particles start to move and therefore will start to become charged [14]. Figure 5(a) shows that at Al Ain, this threshold is $\sim$6 m s^{-1}, above which, the magnitude of the maximum E-field increases with increasing wind speed. This threshold is consistent with many of the values reported in the literature for dust uplift [32]. Figure 5(a) also shows that when the wind speed is >10 m s^{-1}, the gradient of the relationship decreases, suggesting that there is a limit to the magnitude of charge caused by resuspended dust during these events. When the E-field data are binned, figure 5(b) demonstrates a very clear relationship between the maximum E-field ($E_{\max}$) and maximum wind speed (V_{w}), which can be represented by a linear approximation as

$$E_{max} = -1310V_w + 7561 \qquad (1)$$

for $E_{\max}$ in V m^{-1} and V_{w} in m s^{-1}. This equation is calculated from only the inner part of the data (i.e. between wind speeds of 6 and 10 ms^{-1}), and the R^2 value for the fit to the data is 0.99.

As the wind speed increases, and dust begins to be lofted, the visibility starts to decrease. The relationship between the minimum detected visibility (X_{r}) and $E_{\max}$ during the sea breeze front passage is shown in figures 5(c) and (d). Figure 5(d) demonstrates that the relationship between the two is exponential in nature, for which a statistical fit can be found as

$$E_{max} = -5300X_r^{-0.442} \qquad (2)$$

where $E_{\max}$ is in V m^{-1} and X_{r} is in km (R^2 value of the fit is 0.93). Previous work has demonstrated a relationship between the magnitude of the E-field and dust concentration inside dust storms, as, at

[1] It should be noted that this is likely to under-represent the actual number of sea breeze days due to some events which do not produce noticeably large E-field changes, (i.e. as opposed to detection by wind speed or direction changes), which is more likely to be around 70%–80% [20].

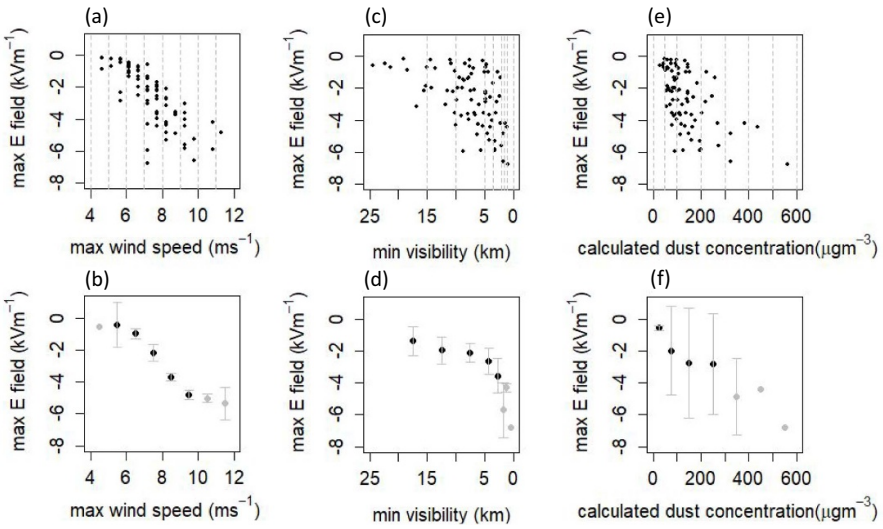

Figure 5. Relationships between maximum Efield and maximum wind speed ((a) and (b)), minimum in visibility ((c) and (d)), and dust concentration ((e) and (f)) during the passage of 80 sea breeze fronts at Al Ain. Plots (a), (c) and (e) show raw data (1 point per event), and (b), (d) and (f) show the medians of the data binned according to wind speed, visibility, and dust concentration respectively. Horizontal grey arrows in (a), (c) and (e) show the bin widths used in (b), (d) and (f); vertical grey arrows in (b), (d) and (f) show 95% confidence limits on the medians of each bin. Dust concentration is estimated from the visibility, using the relationship in Judger *et al* [33]. Grey points denote bins where fewer than 4 data points were available.

greater dust concentrations, reduction in mean free path leads to more collisions associated with more triboelectrification. The exact form of the relationship varies, however, (e.g. Esposito *et al* [12] show an approximately linear relationship between the two for individual events, whereas Williams *et al* [34] show a general increase in E-field change for an increase in dust mass loading, but no clear relationship). Although dust concentration was not measured directly during this study, it is possible to estimate this from the visibility measurements, due to the close exponential relationship between the two parameters [33, 35, 36]. Figures 5(e) and (f) show the dust concentration calculated from visibility, according to the relationship in Judger *et al* [33], which was derived from 4 years of data in the Gobi desert (where dust concentration (μg m^{-3}) = 485.67 X_r $^{-0.776}$ (with visibility X_r in km)). It should be noted that there are many derived relationships between visibility and dust concentration in the literature (see [35] for a summary). Here we use the one from Judger *et al* [33], as it used visibility measured from automatic Meteorological Optical Range sensors (similar to those deployed during this study), rather than manual observations, which can be more subjective. As the visibility and dust particle measurements were made at a height of 2–3 m above the surface, the dust concentration calculated is taken to represent the dust concentration at the approximate height of the field mill (at 3 m).

From the binned data in figure 5(f) a linear relationship between E-field and dust concentration (N_d) emerges, with the following properties:

$$E_{max} = -10.04N_d - 804 \quad (3)$$

where E_{max} is in V m^{-1} and N_d is in μg m^{-3} (R^2 value of the fit is 0.91). It should be noted that the visibility to dust concentration conversion depends on many factors (including particle size), and therefore is a locally derived fit. Whilst the relationship is useful in general terms, its quantitative applicability in other situations may be limited.

The derivation of such relationships in dust storms is difficult due to the complexity of the dust storm environment and sea breeze fronts as used here provide a more consistent situation. Such derived relationships allow estimation of the magnitude of dust charging events at sites where no direct electrical measurements are made, but for where meteorological parameters such as wind speed are known.

5. Discussion

The data presented here demonstrate the ability of the sea breeze front to generate substantial magnitudes of charge through lofting of dust. At Al Ain the polarity of the charge observed during the passage of each of the 80 sea breeze events was positive (i.e. negative E-field) in every single case. This is the opposite polarity to many previous measurements of E-field reported in dust storms in the literature. Existing triboelectrification theory treats the transfer of charge between dust particles during collisions as a size-dependent process, i.e. the larger particles (which are restricted to a shallow (<1 m) layer close to the surface) are likely to charge positively, and the smaller particles (which are lofted by turbulent processes) will charge negatively [4, 37]. The height of the field mill in this case is 3 m with theory suggesting negatively charged particles at this height, which is opposite to what is consistently observed at Al Ain. Two possible explanations are:

(1) Transfer of charge between dust particles is dependent upon local composition/mineralogy (rather than just size), as suggested by Kamra [15], who found predominantly negative E-fields when the dust was comprised of clay minerals, whilst positive E-fields occurred for silica type particles. The regularity of the direction of the sea breeze, and fact that the polarity of the charge generated is always positive, could indicate that the dust is always lofted in the same approximate location, and therefore the local mineralogy determines charging. Of the limited information available on the mineralogy of UAE dust, Hamdan *et al* 2016 [23] report that quartz, calcite, gypsum and sea salts are present in the Sharjah region (north of Dubai) during dust storms, but it is unknown how widely representative this is, or whether the dust considered is of local origin or transported from elsewhere.

(2) Charge is mixed vertically as opposed to simply being generated in the saltation layer [31], thereby distinct regions of charge separation occur. It is generally accepted that the density current/gravity current nature of the sea breeze gives rise to regions of vertical uplift at the sea breeze front, where the two densities of air meet [38]. Such vertical lift initiated or enhanced by the sea breeze front can cause convective clouds, and even thunderstorms [38]. The aircraft measurements of Finkele *et al* [39] over south Australia measured a clear circulatory pattern within the sea breeze front, with updrafts up to 0.5 m s^{-1} at the head of the front, extending to 300 m in altitude. This is also supported by the modelling studies of Talbot *et al* [40] who, using the Meso-NH model, found updraft speeds up to 1.4 m s^{-1} up to 700 m altitude within the frontal region of a sea breeze in the North Sea. It is therefore possible that the thermal and mechanically driven turbulence in the sea breeze front at Al Ain generates an upward flow which transports the positively charged particles to a higher altitude, perhaps forming a stable layer of positive charge at the approximate height of the field mill, in a repeatable manner during every sea breeze event. The observation that only the sea breeze front yields substantial E-field changes supports this conclusion, as this is likely to be the main area of substantial vertical motion within the sea breeze structure, where active separation of charge takes place. In the case study presented in figure 2, some dust is clearly present in the lower boundary layer for many hours following the sea breeze front passage, as seen by the ceilometer. The lack of vertical mixing within this layer means that, even though the dust particles near the surface may be lofted and become charged through contact charging and triboelectrification within the saltation layer, no substantial E-fields will occur as no large-scale charge separation takes place.

Most previous measurements of negative E-fields in dust storms have been reported alongside positive ones (i.e. the polarity of the E-field is variable). This has been explained by the vertical mixing of charge in strong gust fronts associated with the dust storms, which lofts the large positively charged particles, as well as the small negatively charged ones and mixes them together. Examination of the entire Al Ain E-field dataset for 2018 shows only two occurrences of positive E-fields during the dust storms which are not linked to sea breeze effects. During these events, the E-field was still predominantly negative, but with short periods of positive E-field. It is likely that the dust storm episodes were much more variable in their vertical wind structure than the sea breeze case, therefore variable polarity charge within a dust storm may be expected from additional vertical mixing.

These observations at Al Ain add to the growing number of such measurements in dusty conditions [12, 15, 41] and demonstrate that the simple expectation that E-fields in dust storms are predominantly positive is incomplete. It is likely that the altitude at which the E-field is sampled is critical in determining the polarity (as demonstrated by [42]). If the origin of the dust charge is primarily from interactions within the saltation layer, with charged particles transported upwards due to turbulent mixing, multiple simultaneous E-field measurements at different heights will be necessary.

6. Conclusion

These measurements demonstrate that in arid environments, away from coastal locations, sea breeze fronts can generate significant levels of charge, causing surface E-field as large as -7 kV m^{-1}. The Efield measurements reported are the first to be made in the United Arab Emirates, and this is the first paper to report on significant E-fields present in sea breeze fronts away from bodies of water. The large E-fields arise from interactions between dust particles, lofted upwards as the sea breeze front travels across a dry surface. Large E-fields are only observed during the passage of the sea breeze front itself (and not in the following dust layer), therefore the updrafts in the frontal region are likely to be key in providing a mechanism for charge separation. The signature and magnitude of the electrical changes are such that the arrival of the sea breeze front can be detected by electrical measurements alone (rather than the traditional meteorological wind speed and direction measurements), with an electrically active sea breeze being detected at Al Ain on 40% of days in 2018. The E-field becomes strongly negative (i.e. greatly increasing the negative E-field present during fair weather) during all of the 80 detected sea breeze front arrivals considered, in contrast to the often reported positive E-field changes in the literature associated with dust storms. This points to either the polarity of the charge separation being different in this location, or, more likely, the regular structure associated with a low level sea breeze front consistently envelopes the sampling

instrument with the same polarity. From the repeatable electrical changes associated with the sea breeze front, clear and unambiguous relationships have been derived between E-field changes and wind speed, visibility and dust concentration.

Understanding the processes which give rise to dust electrification is a challenging problem, which has mostly been investigated in complex situations such as dust storms and dust devils, which occur on a sporadic basis. The identification here of the sea breeze front as an effective generator of large E-fields in dusty regions presents a simpler dynamical system in which to study dust electrification processes. It also demonstrates that dust charging is a much more widespread and frequent phenomenon, which is not only associated with irregular dust storms. Electrification of dust has widespread implications for measurements of dust concentration, which rely heavily on satellite data and the assumptions made in the retrieval processes. The magnitude of E-fields reported here are large enough to affect the orientation of dust particles as suggested by Ulanowski *et al* [10], and are likely to also affect the uplift of dust from the surface (e.g. Esposito *et al* [12]), effects currently unaccounted for in radiative transfer modelling and dust source models, which are key to producing accurate models of the climate.

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Data Availability

The data that support the findings of this study are openly available. METAR data was downloaded from https://mesonet.agron.iastate.edu/request/download.phtml?network=AE__ASOS. E-field, visibility and ceilometer data can be accessed from the University of Reading Data Repository at http://dx.doi.org/10.17864/1947.246.

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