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Fair weather criteria for atmospheric electricity measurements

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ABSTRACT

The global atmospheric electric circuit, which links the space environment with terrestrial weather, has mostly been investigated using fair-weather surface atmospheric electricity measurements. Retrieving global circuit information, however, requires the selection of "fair weather" data, to avoid local meteorological disturbances. The research results presented here challenge the applicability of long-standing definitions of electrically fair weather atmospheric conditions. From detailed new measurements and theory, three improved requirements (FW1 to FW3) for fair weather atmospheric electricity conditions are described. These are: (FW1) absence of hydrometeors, aerosol and haze, as apparent through the visual range exceeding 2 km, (FW2) negligible cumuliform cloud and no extensive stratus cloud with cloud base below 1500 m, and (FW3) surface wind speed between 1 m s^{-1} and 8 m s^{-1}. Automatic and manual measurement approaches to identifying these requirements are given. Through applying these criteria at the many measurements sites now operating, the noise from meteorological variability will be reduced, leading to data more representative of the global electric circuit.

1. Introduction

Surface atmospheric electricity measurements, typically those of the vertical electric field and the vertical current density have been made during the past 150 years, and are often undertaken to obtain information on the global atmospheric electric circuit. The global circuit concept, originated by CTR Wilson (e.g. Wilson, 1929), retains much value for understanding electric current flow in the troposphere (Rycroft et al., 2000, 2012; Tinsley, 2008). Some global circuit quantities are less sensitive to local effects than others, such as the positive potential at about 10 km above the surface (Markson, 2007). Although this potential is essentially a global parameter, it is not routinely measured because of the need for an ascending platform from which to make the measurements. In contrast, surface measurements are more abundant and readily obtained, but the global circuit influence is likely to be obscured in them by local factors such as aerosol pollution, radioactivity or meteorological disturbances.

Improvements in technology have contributed to renewed interest in providing atmospheric electricity measurements at many sites internationally. The GLOCAEM (GLObal Coordination of Atmospheric Electricity Measurements) project[1] is specifically intended to bring together many of the disparate sets of near surface atmospheric electricity measurements, as the lack of such data has been a major limitation for research in fair weather atmospheric electricity. It is therefore timely to consider how such data should be selected to minimise local effects. In this paper, considerations for effective data selection are discussed and the principal selection criteria identified.

The most commonly measured surface quantity in atmospheric electricity is the vertical electric field or Potential Gradient (PG), which represents the difference[2] in potential between two vertically separated points, the lower of which is typically the surface itself. This atmospheric property has been observed using a range of experimental techniques since the late 1700s (Chalmers, 1967; Israël, 1970). During the 1800s, such observations became increasingly systematic, most notably through Lord Kelvin's invention of the "water dropper" potential equaliser, implemented with photographic recording (Aplin and Harrison, 2013). Such a system was first installed at Kew Observatory, near London, in 1861 (Everett, 1868; Harrison, 2006). The Kelvin instrumentation became widely used, including during the 1890s for above-surface measurements on the Eiffel Tower (Harrison and Aplin, 2003) and in instrumented balloons from Salzburg (Tuma, 1899; Nicoll, 2012), as well as at the Scottish observatory of Eskdalemuir from 1910 to the 1930s (Harrison, 2003). As the practice of recording hourly PG measurements became more widely adopted at other sites, radioactive probe sensors were employed as they provided greater convenience compared with the Kelvin water dropper, for example at Porto Observatory (Portugal), Nagycenk Observatory (Hungary) and Lerwick Observatory (Shetland). Use of Kelvin water dropper technology

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[1] https://glocaem.wordpress.com.

[2] For a vertical component of the electric field E_z, the potential gradient F is given by $F = -E_z$. This sign convention is adopted so that, in locally undisturbed (fair weather) atmospheric electrical conditions, F is positive.

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continues at Kakioka Magnetic Observatory in Japan (Takeda et al., 2011).

Broader applications of PG measurements exist beyond investigating the global circuit. Past observations of PG at highly polluted sites have been interpreted as historical proxy air pollution measurements (Harrison, 2006; Aplin, 2012), as the PG increases in proportion to the aerosol concentration (Harrison and Aplin, 2002). Measurements of PG also respond sensitively to increased environmental radioactivity, which acts to reduce the PG (Hamilton, 1965; Pierce, 1972; Takeda et al., 2011). Fair weather PG observations can also provide a sensing method for obtaining characteristics of the atmospheric boundary layer (Anisimov et al., 2017, 2018).

Developments in electronic technologies now allow PG measurements to be obtained relatively easily using electric field mills. Field mills are robust instruments operating on electrostatic principles, often intended for lightning warning applications but nevertheless sufficiently sensitive to provide measurements in the much weaker electric fields necessary for global circuit analysis. Many field mills are also able to run continuously in hostile conditions, such as snow and heavy rain.

Before considering the perturbing effect of local conditions, it is important to point out that the absolute value of PG from a field mill, radioactive probe or Kelvin water dropper is affected both by the physical environment around the sensor as well as by the calibration of the sensor itself. Metal masts or guy lines act to distort the electric field environment, and therefore modify the PG which is measured. For PG measurements to be comparable with those at other sites, and remain independent of long-term changes occurring at the measurement site itself, the PG measurements need to be standardised to an open situation where there are no distorting effects. Methods for achieving this are briefly summarised in the Appendix.

In the following sections, previously-used criteria for fair weather data selection of PG are discussed (section 2). Section 3 presents new insights into local meteorological influences on PG, and section 4 proposes refined fair weather criteria, building on the additional information available through new high sampling rate PG measurements and modern instrument developments.

2. Data selection approaches

Approaches already used to select PG measurements are now summarised. Whilst ultimately the local effects on the PG at a site are random in some respects, allowing a mean global signal to emerge by averaging (e.g. for obtaining the diurnal cycle), the principle behind data selection is pragmatic, which is to reduce the amount of random local noise in the data through first removing values clearly dominated by local influences. This should provide the most effective use of the measurements made in exploring the related geophysical influences and phenomena.

2.1. Electrical character method

As mentioned above, many early installations of PG instrumentation apparatus occurred at existing geomagnetic observatories. Even the PG measurements made during the cruises of the survey ship *Carnegie,* of huge importance through their role in establishing the globally-synchronised single maximum in the diurnal variation of PG, arose from plans for a survey of geomagnetic measurements (Harrison, 2013). The geomagnetic heritage was influential. Daily geomagnetic recordings were originally classified by how disturbed they appeared in terms of the variability of the quantities measured: days were simply described as “Quiet” or “Disturbed”. It is therefore perhaps not surprising that a similar approach to classification was initially applied to the atmospheric electricity records, in which variability was a known characteristic feature, famously remarked on by Lord Kelvin (Aplin and Harrison, 2013). The Carnegie Institution classified their PG data in this geomagnetism-inspired approach, as did the UK Met Office (UKMO).

Table 1
Met Office “electrical - character figure” classification system for daily Potential Gradient records.

First character	Requirement
0	**No negative PG measured**, midnight to midnight
1	**One or more negative PG measurements**, in total for less than three hours
2	**Negative PG measured**, with total duration longer than three hours
Second character	**Requirement**
a	**PG always less than 1000 V m^{-1}** throughout all 24 periods of one hour
b	PG greater than 1000 V m^{-1} for less than six individual hours
c	PG greater than 1000 V m^{-1} for more than six individual hours

The UKMO character system classified a day with solely positive PG values as of type “0”, with “1” or “2” applied to days with increasing negative PG durations. A letter was added after the number to indicate the range of PG values (see Table 1).

Much as the “electrical character” classification system does serve to organise PG data, and was very effective in identifying the days used for further analysis from the *Carnegie* cruises, it leads to an inefficient use of data at sites which are subject to frequent weather disturbances. As an illustration, consider the case of a brief thunderstorm lasting an hour in an otherwise calm day. This would cause the UKMO character scheme to classify the whole day as disturbed or even highly disturbed, despite the fact that, for almost all the hours of the day, the conditions were not disturbed. Those undisturbed data values may nevertheless still contain globally-pertinent information.

2.2. Fair weather method

At Lerwick Observatory, where the weather is highly variable, the electrical character system was used from the outset of the site's measurements in January 1927 (Harrison and Nicoll, 2008). From January 1957, a modification was made in that only hours without precipitation were considered in obtaining the mean daily values. Further, from January 1964, a new selection system was employed experimentally, which classified values on an hour by hour basis, rather than using a single description for the entire day. An important aspect was that this classification was not made on the basis of the measured quantity itself, which can be regarded as effectively an arbitrary selection and therefore open to criticism, but by applying independent criteria based on the local meteorological conditions. To achieve this, hourly PG data values were individually designated as having “no hydrometeors” (i.e. no rain, hail or snow), or “fair weather” (OYB, 1922–1967).

Values identified as having been obtained during fair weather in the later period of the Lerwick site's operation during the 1970s show, on further processing, both a Carnegie curve diurnal variation (Harrison and Nicoll, 2008), and a relationship with sea surface temperatures modulated by El Niño (Harrison et al., 2011). These independent findings indicate that the hourly designation approach to data selection can be considered successful in extracting globally-relevant information.

To classify the hourly data values as having occurred during fair weather, the UKMO originally required that the following **four** meteorological criteria[3] were fulfilled:

[3] These criteria were based on recommendations from a working group of the Joint Committee on Atmospheric Electricity, formed from the International Association of Meteorology and Atmospheric Physics (IAMAP) and the International Association of Geomagnetism and Aeronomy (IAGA).

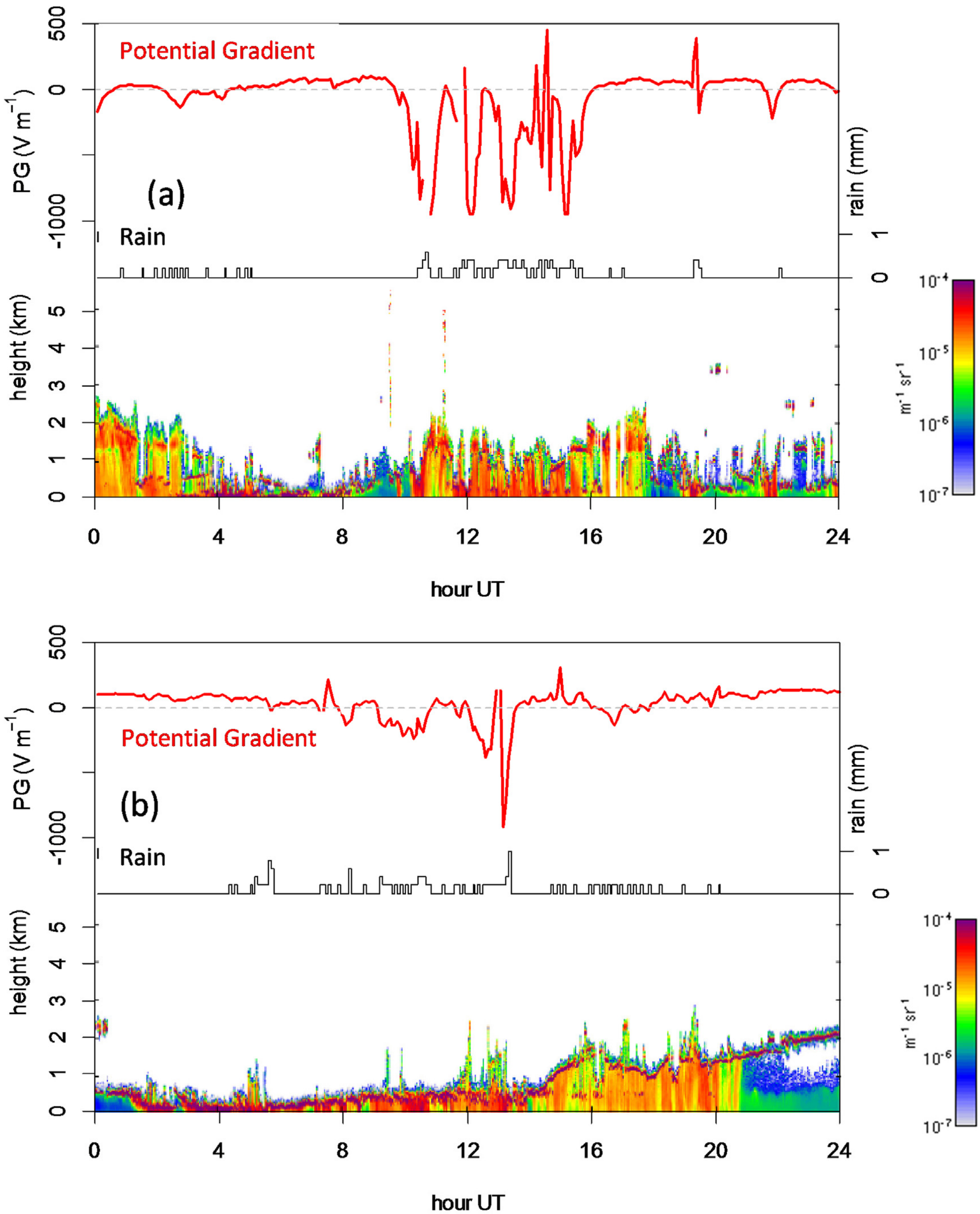

Fig. 1. Time series of Potential Gradient, rainfall and ceilometer backscatter, as found at Reading University Atmospheric Observatory, UK for two days with showers, (a) 15th April 2016 and (b) 9th Aug 2017. In each case the upper panel shows the PG time series as 5 min average values from 1 s samples, the middle panel the rainfall amounts in the same 5 min periods, and the lower panel the time series of the vertical profile of the attenuated backscatter coefficient from a Vaisala CL31 ceilometer.

(1) no hydrometeors
(2) no low stratus cloud (cloud base above 300 m at Lerwick)
(3) up to three-eighths cumuliform cloud as long there is no effect on the PG record, or no more than one-eighth if there is an effect
(4) mean hourly surface wind speed (measured at 10 m) less than 8 ms^{-1}, (or Beaufort force 5).

These four criteria identify local factors which may seriously influence PG measurements. Criterion 1 seeks to avoid the effects of bad weather associated with the presence of liquid or solid precipitation, which may include strongly charged clouds or charge released from the splashing of droplets or the melting of hail or snow. (This was also regarded as the minimum criterion for useful measurements, as, if only this condition was met, the hourly PG value was recorded, but marked as an hour of no hydrometeors instead of fair weather.) Criterion 2 seeks to avoid effects of fog or very low cloud. Criterion 3 is intended to avoid the large influences which can readily arise from strongly electrified convective cloud. Criterion 4 reduces the local effects associated with the re-suspension of dust and snow, which may transport charge, as well as minimising displacement currents generated by blowing space charge. Clearly there may be some overlap between the categories. For example, Criterion 4 will also provide additional (or early)

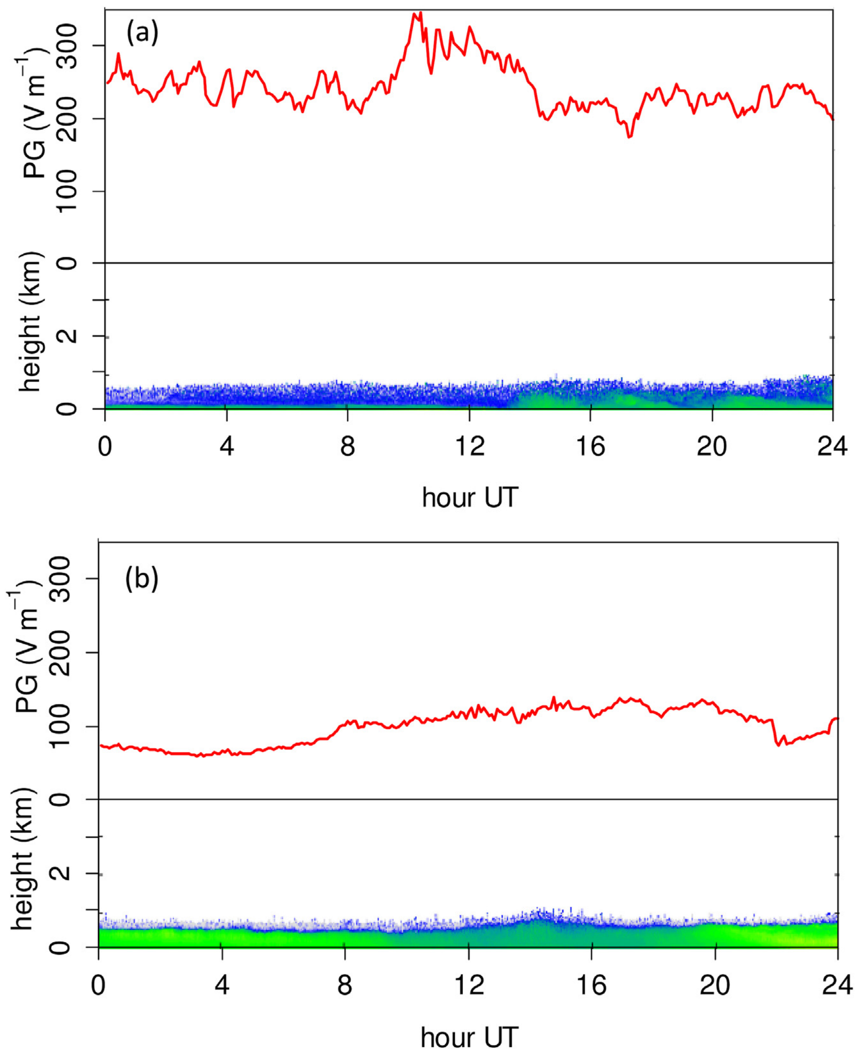

Fig. 2. Daily time series on clear days of ceilometer backscatter profile (lower half-panels) and PG (red trace, upper half-panels, 5 min means from 1 s samples) obtained at Reading University Atmospheric Observatory, for (a) 20th January 2016 and 25th November 2016. The ceilometer colour scale is the same as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

identification of periods of bad weather concurrent with Criterion (1), and failures to meet criteria (1) and (2) may also occur simultaneously.

Similar approaches have been used at other sites,[4] based on the absence of clouds, precipitation, fog, dust and strong winds (Imyanitov and Shifrin, 1962). Particular attention has also been given to sites in Antarctica. Deshpande and Kamra (2001) considered that fair weather conditions existed when there was no rain or snowfall, the wind speed was less than 10 ms^{-1}, there were no low clouds and there was less than 3 oktas of high cloud. Minamoto and Kadokura (2011) showed that local effects were minimised for wind speeds less than 10 ms^{-1} and total cloud amounts of less than 10%. Siingh et al. (2013) also made fair weather data selection by requiring wind speeds less than 10 ms^{-1}.

2.3. Other methods

Whilst the UKMO classification method is appealing because of its efficient use of hourly data, there are other methods which have yielded some benefit. Restricting data to the relatively undisturbed times of day at a specific site, for example before dawn, can yield values less affected by local factors. Märcz (1997) used this approach to identify Forbush effects (a sudden reduction in galactic cosmic ray ionisation of heliospheric origin) on the surface PG measured at Nagycenk Observatory by using early morning data. Other approaches which can be used without concurrent meteorological data is to restrict the PG values to those falling within a range considered typical of fair weather conditions (Adlerman and Williams, 1996; Burns et al., 1995; Harrison and Nicoll, 2008; Nicoll and Harrison, 2009). Harrison and Märcz (2007) combined both the undisturbed period and restricted range methods to detect a spectral feature characteristic of the heliosphere in the Nagycenk PG data.

As mentioned above, PG measurements in polar environments have often been selected for fair weather on the basis of meteorological conditions differing from the standard UKMO criteria, including restricting data to conditions when the relative humidity is relatively constant, and excluding certain temperature ranges (e.g. around 0 °C, when phase changes can cause instrumental problems) (Burns et al.,

[4] Observatory reports from Swider, Poland, refer to a 1965 document *Instruction on preparation of the material and publication of the results of atmospheric electric observations*, issued by the Aleksandr Ivanovich Voeikov Main Geophysical Observatory (MGO) in Leningrad. For electrically fair weather conditions, no negative PG, no PG exceeding 1000 Vm^{-1} and low cloudiness less than 3/10 were required, together with no precipitation, fog, mist, local or distant thunderstorm (Odzimek, 2018).

1995). Fast changes (or spikes) in PG or variability more rapid than the time constant (~15 min) typical of the global circuit have also been used to identify and eliminate local influences (Burns et al., 2005, 2017). Finally, for sites where local pollution sources are known to originate from certain directions it is also necessary to exclude such wind directions from analysis (e.g. Hamilton, 1965; Burns et al., 1995; Frank-Kamenetsky et al., 1999).

3. Investigations of electrically-disturbing meteorological factors

The UKMO fair weather criteria indicate a role for cloud and wind speed in disturbing the surface PG defining the less disturbed conditions, and although not explicitly identified in the criteria, the effects of surface aerosol are also expected to be important (Harrison and Carslaw, 2003). Automated instruments are now available which allow further investigation of these effects. A ceilometer has been found particularly useful for identifying periods of rainfall, cloud and fog and "Present Weather" sensors are also available which seek to classify conditions through visual range or other measurements.

Ceilometers typically use an upwards pointing infra-red laser to determine the vertical profile of backscatter up to many kilometres above a site. The backscatter signal occurs from aerosol, water droplets or ice, and hence allows the presence or absence of clouds to be identified, together with the height of the cloud base. Ceilometer data can be presented as a time series, for example showing the variation in the vertical profile of backscatter across a day. Cloudy conditions can then be identified, and the cloud duration and cloud base duration determined. The attenuating effect of water droplet clouds on the laser beam is such that, if cloud is present, only the lower edge of the clouds is identified, with little else able to be detected above the cloud base unless the cloud is broken.

3.1. Rainfall

In selecting PG data for the least effect of local disturbances, precipitation is almost certainly the most important factor to exclude. The effects of rainfall are so substantial that this is readily illustrated using ceilometer measurements which show both the cloud base position and strong backscatter returns from the rainfall itself. Data from two days (15th April 2016 and 9th August 2017) at Reading, UK, having prolonged periods of rain and intermittent showers are shown in Fig. 1, combining the PG measured by a JCI131 field mill with backscatter time series obtained from a Vaisala CL31 ceilometer and rainfall from a tipping bucket rain gauge. The daily rainfall totals were 16.8 mm (15th April 2016 in Fig. 1 (a)) and 17.2 mm (9th August 2017 in Fig. 1(b)).

On both days, the profound effect of the rainfall on the PG measurements is apparent, frequently leading to negative PG values extending to $-1000\ \mathrm{Vm^{-1}}$. Using the character figure descriptions of Table 1, these days would be classified as highly disturbed, such as class 2b or 2c. However, between the rainfall events and in the last hours of both days, small positive PG values return, illustrating the usefulness of identifying the undisturbed periods, even on days with substantial rainfall such as these.

3.2. Clear days

On clear days, the variations in PG are much reduced, and without the strong excursions on a day with rain. Fig. 2 shows PG and ceilometer data from Reading, for days devoid of cloud throughout. Weak backscatter returns are apparent in the atmospheric boundary layer (typically below 1 km), which, in the absence of cloud, is interpreted as occurring from near-surface aerosol. Despite the superficial consistency in the meteorological conditions from the clear skies, the PG data values

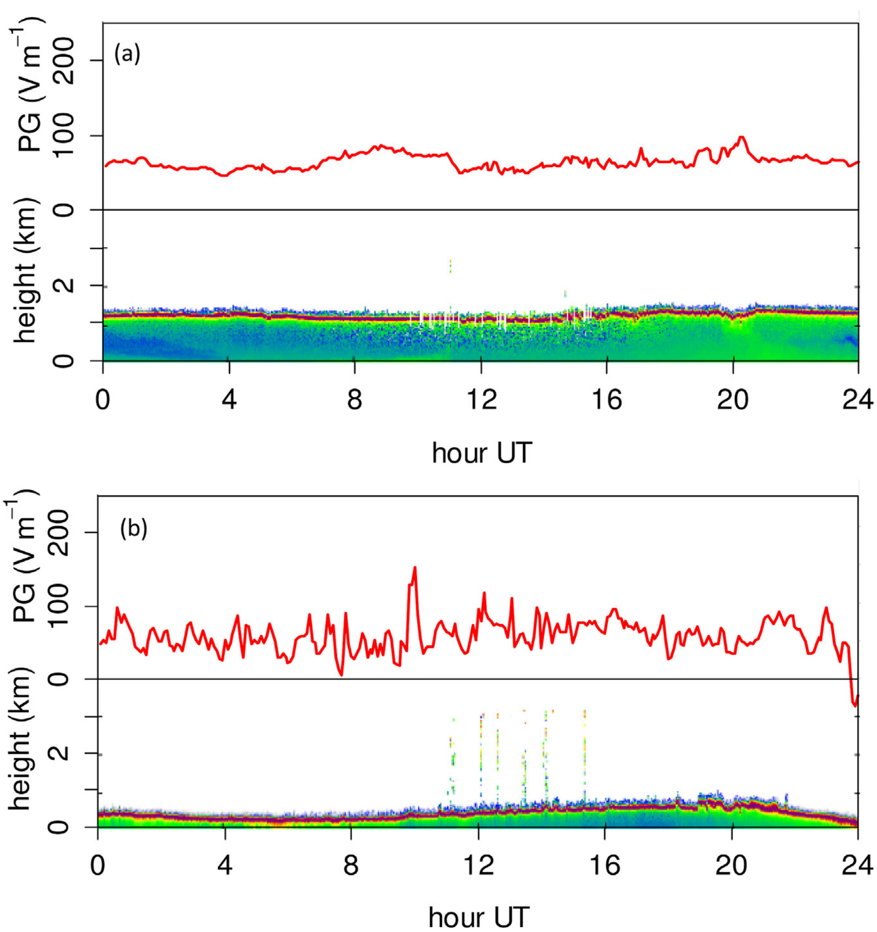

Fig. 3. Daily time series on cloudy days of ceilometer backscatter profile (lower half-panels) and PG (5 min means from 1 s samples) obtained at Reading University Atmospheric Observatory, for (a) 23rd March 2016, and (b) 3rd June 2016. The ceilometer colour scale is the same as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

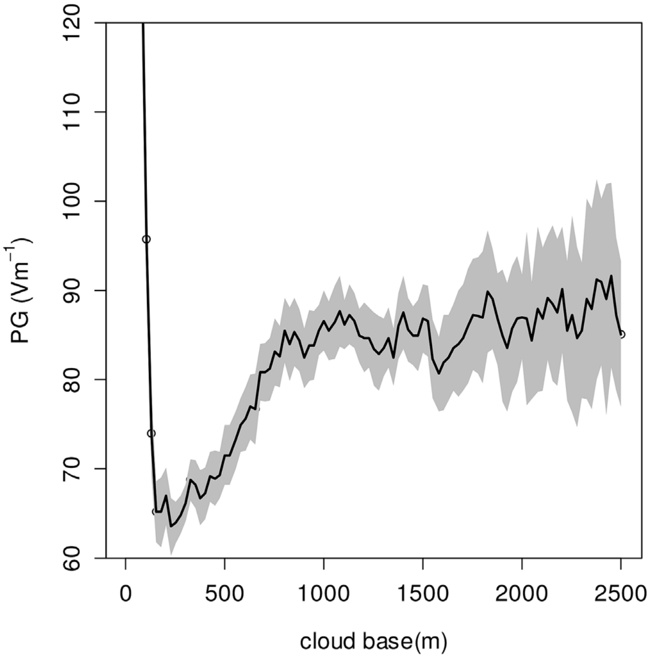

Fig. 4. Cloud base height values plotted against PG using 5 min average values at Reading during Jan 2015–Dec 2017, (198688 values). The black line shows the median PG calculated for the associated cloud base values binned into steps of 25 m, where grey bands denote 95% confidence limits.

show markedly different characteristics in their mean value and the timescales of the variability. Clear sky conditions alone are therefore insufficient to identify fair weather conditions suitable for global electric circuit considerations.

3.3. Layer clouds

The UKMO criteria specifically identify small amounts of convective cloud or low level layer clouds as invalidating the fair weather condition. This is, in part, because the lower edges of layer clouds can become charged. For a layer cloud to become charged by the global circuit, it must be sufficiently extensive for the conduction current to pass through it rather than around it, which in general requires the sky to be entirely overcast (see e.g. Zhou and Tinsley, 2007; Nicoll and Harrison, 2016). Fig. 3 presents PG and ceilometer data from days with extensive layer clouds at two different heights. In Fig. 3(a) the cloud base is above 1 km and there is little associated variability in the PG data, whereas in Fig. 3(b) the cloud base is well below 1 km, and the PG variability is substantial. The full dependence of the PG on cloud base height for extensive layer clouds is demonstrated in Fig. 4 which shows a suppression of the PG for cloud base heights between 0.1 and 1 km (due to negative charge in the cloud base, which is close enough to affect the field mill measurements (Harrison et al., 2017). For cloud bases above this height there is little effect of the cloud on the PG. (The large PG values on the far left of Fig. 4 occur during fog conditions (cloud base < 0.1 km), which are well known to increase the PG through a reduction in conductivity). The cloud base height is therefore an important consideration, and evidently the original UKMO cloud base requirement of 300 m or above is insufficient to ensure there are no effects on the surface PG when there is extensive low level layer cloud.

3.4. Effect of wind speed

Although the UKMO fair weather criteria specify a maximum wind speed, a minimum wind speed is not given. This deserves further consideration, as, in low wind speed conditions, charged aerosol may accumulate near the PG sensor, which will disperse under greater ventilation. Some further insight into the variability of the PG across the clear and cloudy days examined above can be obtained through examining the wind speeds on relatively clear and cloudy days.

Fig. 5 shows the relationship between near-surface wind speed (u_2) and PG at Reading, using the daily medians of each variable to remove diurnal cycle effects. In Fig. 5(a) data are shown for days with hardly any duration of cloud as determined by the ceilometer, and in Fig. 5(b), for days with appreciable cloud. Although there are few clear or almost-clear days compared with the cloudy days, the form of the response is similar in both cases, showing that the presence or absence of cloud is not important. For small wind speeds (u_2 < 0.5 ms^{-1}), the PG increases substantially with decreasing wind speed, whereas for modest wind speeds (u_2 > 1 ms^{-1}), the PG tends to a steady value with little sensitivity to wind speed.

3.5. Decreases in visual range

Fog at the surface reduces the air's electrical conductivity, which, under conditions of constant vertical conduction current, leads to an increase in the PG. Fog is usually clearly apparent in ceilometer data because of the substantial near-surface attenuation it causes, with hardly any backscatter return from above. Fig. 6 shows two example days from Reading during which fog formed overnight, and then lifted

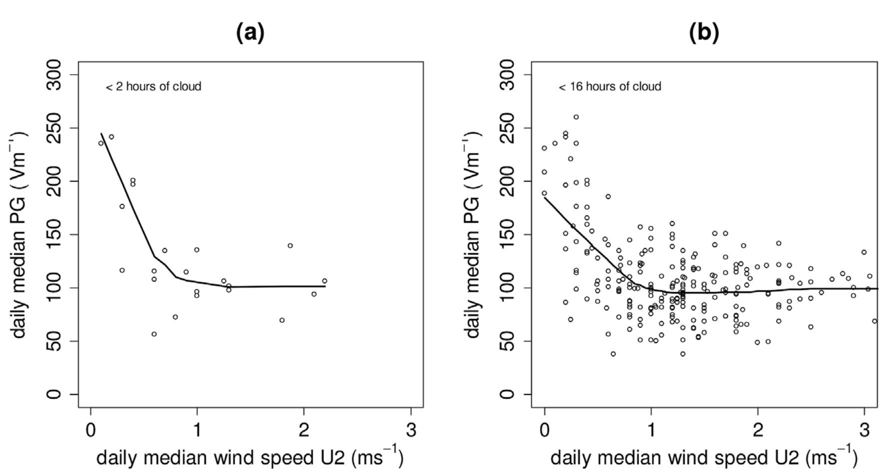

Fig. 5. Daily median values of Potential Gradient (PG) against wind speed at Reading measured at 2 m (u_2) during 2015–2017, for (a) days with less than 2 h of cloud (29 days) and (b) days less than 16 h of cloud (239 days). In each case, a lowess fit line has been added.

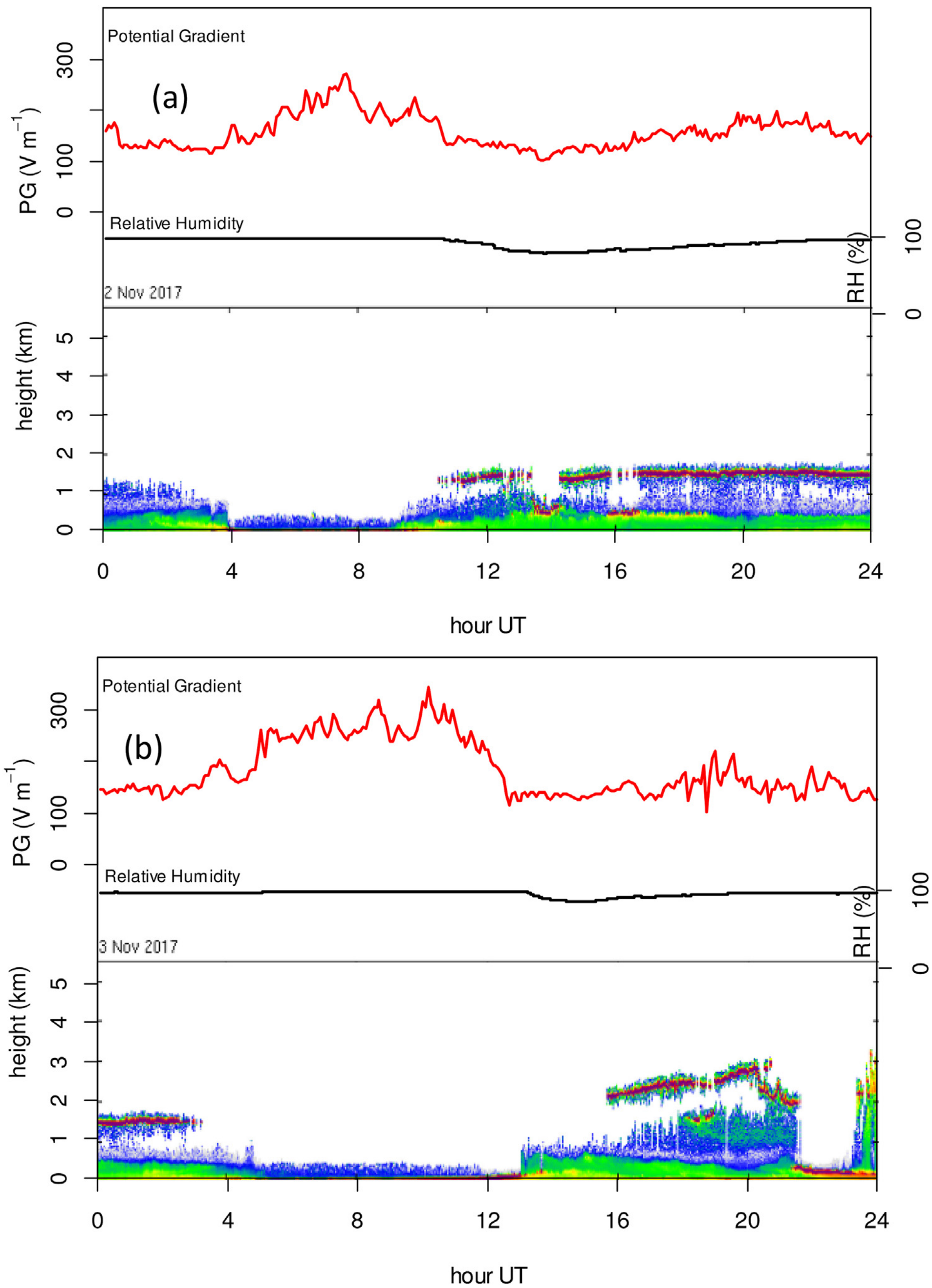

Fig. 6. Variations in Potential Gradient (PG) at Reading (upper panel) for two days with fog, (a) 2nd November 2017 and (b) 3rd November 2017. The relative humidity (RH) data from the site is also shown, and both this and the PG data are five minute average values from 1 s samples. The ceilometer colour scale is the same as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in the morning. During the fog episodes, the PG is increased by 100–200 Vm^{-1} or more, and becomes more variable. Recovery from the enhanced values is relatively rapid, as fog dissipation is often accompanied (or indeed caused) by a sudden increase in wind speed.

An alternative detection method is to measure the visual range, which is markedly affected by fog. This can be determined automatically by an optical scattering device such as a transmissometer or a present weather sensor. Fig. 7 (a) shows the relationship between automatic measurements of visual range and PG, for the days considered in Fig. 6. At small visual ranges (less than 2 km), the increase in PG is very apparent. Theoretical considerations (Harrison, 2012) support the sharp increase in PG at small visual range, and indicate that there is little effect on the PG for large visual ranges. In such calculations, the final asymptotic PG value for large visual ranges is set by the choice of properties (size and concentration) of the background aerosol.

Decreases in visual range can also result from falling or blowing precipitation (particularly snow), as well as lofted aerosol or dust. Fig. 7(b) shows the dependence of PG on visual range during blowing snow conditions at Halley, Antarctica (selected on the basis of wind speed > 7.5 ms^{-1}). There is a considerable increase (of order of 4–5

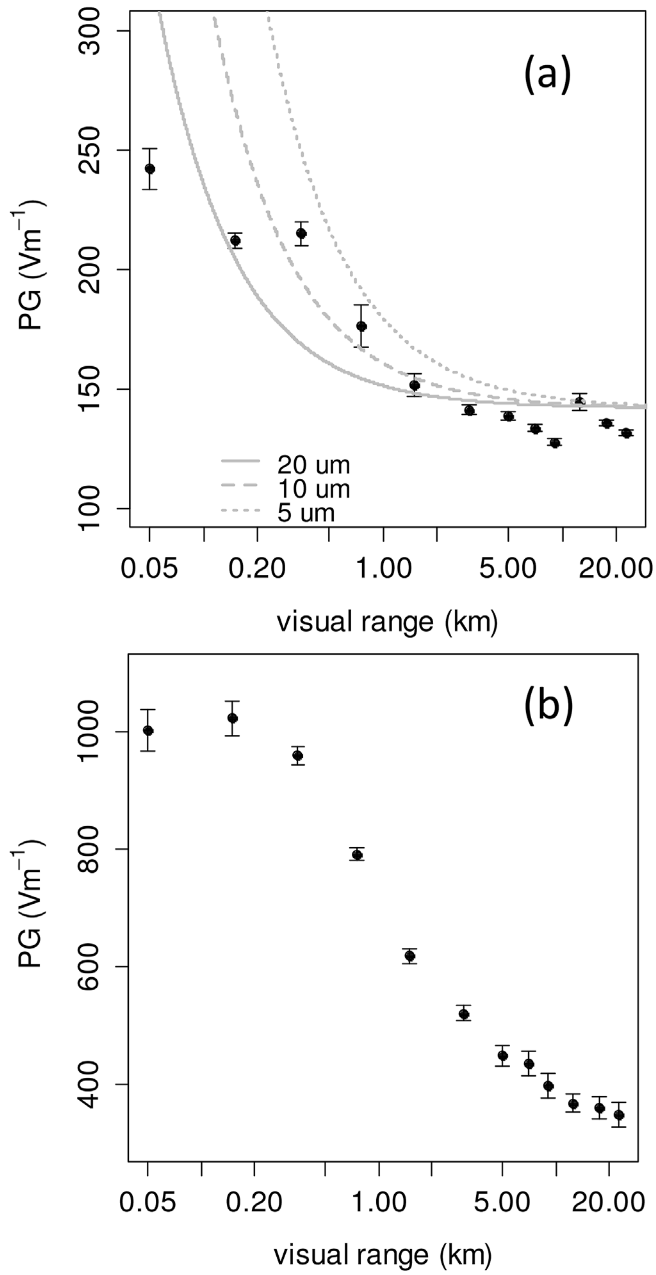

Fig. 7. (a) Relationship between visual range and PG during fog conditions at Reading, UK (during the 2nd and 3rd November 2017 (see also Fig. 6)). The lines shows the theoretical relationship (Harrison, 2012) expected between PG and visual range for a range of fog droplet diameters, assuming a vertical conduction current density $J_z = 2\,\text{pA m}^{-2}$, background aerosol of radius 0.2 μm and number concentration 3500 cm^{-3} and mean ion mobility 1.2 cm^{2}V^{-1}s^{-1}. (b) Relationship between visual range and PG in blowing snow conditions at Halley, Antarctica, for 2 years of data from 2015 to 2016. Blowing snow conditions were selected on the basis of wind speed > 7.5 ms^{-1}. In both plots data points show the median values of PG binned according to visual range (in 12 bins from 0.1 to 25 km). Error bars show 2 standard errors on the mean.

times) in the magnitude of PG during blowing snow compared to fog for visual range values less than 5 km. At relatively large values of visual range (> 15 km) there is still a demonstrable effect on the PG of blowing snow compared to fog, suggesting that the wind plays a considerable role in the transport of space charge in the Antarctic environment.

4. Revised fair weather requirements

Whilst the UKMO fair weather criteria have demonstrated their usefulness in selecting globally-representative data from a site with frequent episodes of disturbed weather, the data presented here indicate that some perturbing atmospheric conditions are not properly identified. Because of the recent increase in interest in PG measurements and the availability of automatic meteorological instruments, some refinements to the UKMO criteria are now indicated, over fifty years since they were first proposed. Of the four UKMO criteria, the first criterion, that there should be no hydrometeors, is the most important and clearly identifiable. The third criterion, of minimal cumiliform cloud is also important, and acts to prevent effects of strongly electrified clouds. The second and fourth criteria are worthy of more scrutiny.

Considering the second criterion first, which requires no low stratus cloud, ceilometer data shows that charging in the cloud base of layer clouds can markedly affect the surface PG, for stratus cloud base heights extending well above the UKMO-suggested minimum height requirement of 300 m. Through considering two years of cloud base data, Harrison et al. (2017) (supported by Fig. 4 in this paper) concluded that charge in the base of layer clouds affects the surface PG by an amount which increases non-linearly with decreasing cloud base height below 1500 m. The cloud base height criterion on low stratus cloud for these purposes therefore needs to be increased to at least 1000 m and preferably 1500 m.

The fourth criterion of a maximum hourly wind speed of 8 m s^{-1} is particularly relevant at some sites where blowing snow or sand is common such as in polar regions (e.g. Corney et al., 2003; Deshpande and Kamra, 2001; Burns et al., 2012), or in dry desert areas (e.g. Elhalel et al., 2014; Yaniv et al., 2016). However, in general, it is also important to ensure that there is adequate surface ventilation to avoid an accumulation of aerosol either in the lower boundary layer or near to the sensor itself, which is not considered in the UKMO criteria. A minimum wind speed of 1 m s^{-1} at 2 m appears sufficient for this.

Effects of haze and dust are not explicitly considered by the existing UKMO criteria, although criterion 4 acts to reduce the possibility of generating blowing snow or sand. The wide variety of possible suspended materials can be addressed by considering the single parameter of visual range, which is estimated at many meteorological sites and for which automatic instruments are now available. Visual range will be reduced in fog, blowing snow or sand, haze layers and in rainfall or snowfall, circumstances in which strong perturbing local effects will occur. Ensuring adequate visual range will therefore eliminate many situations with perturbing hydrometeors and aerosols.

Taking these aspects into account, Table 2 provides a revised summary of the criteria needed to identify fair weather atmospheric electricity conditions. These are expressed as three fair weather requirements concerning (FW1) hydrometeors, haze and aerosol, (FW2) cloud and (FW3) wind, in order of priority. Requirement FW1 addresses the need to exclude conditions with liquid or solid precipitation as well as when there is suspended particulate material in the air. This extends the original UKMO criterion 1 beyond just considering hydrometeors, through adding a visual range requirement, based on the close relationship known between PG, aerosol and visual range (Harrison, 2012). FW2 combines UKMO criteria 2 and 3, with the additional requirement from the analysis of Harrison et al. (2017) that the cloud base should be at least 1500 m. FW3 extends UKMO criterion 4 to

Table 2
Meteorological criteria for identifying fair weather atmospheric electricity conditions.

Weather parameter	Requirement from original Met Office criteria	Reason for requirement	Further points	Alternative criteria from automated measurements	Alternative criteria from basic manual measurements
FW1: aerosol	No hydrometeors of any kind	No charge released from rainfall No charging from snow or hail	Minimise the effect of haze layers, local aerosol, lofted dust or blowing snow	Require visual range 2 to 5 km or greater (Harrison, 2013) Relative Humidity (RH) $<$ 95%	Dry for the period in question Visual range $>$ 2 km
FW2: cloud	No low stratus cloud A maximum of 3 oktas of cumuliform cloud, or no more than 1 okta if electrical effects are apparent.	Prevent strongly electrified clouds from influencing the surface measurements Avoid the air conductivity reduction associated with surface fog.	No stratus or stratocumulus cloud with cloud base below 1500 m (Harrison et al., 2017)	Diffuse fraction (S_d/S_g) $<$ 0.4 (Harrison et al., 2008) if there is no cloud base height information	No low stratiform cloud or fog, and no convective cloud
FW3: wind speed	Wind speed less than 8 m s^{-1} measured at 10 m, i.e. $u_{10} < 8$ m s^{-1} (equivalent at 2 m, to $u_2 < 7$ m s^{-1})	Avoid lofting of dusts, blowing snow, fluctuations from dispersion of charged particles and displacement currents from transport of space charge. Note that radioactive probe needs small wind speeds (~1 to 3 m s^{-1} at probe level depending on the amount of radioactivity), to allow equalisation	To minimise the possibility of persistent charged layers ensure a minimum wind speed occurs, $u_2 > 1$ m s^{-1} (at 2 m)	Wind speed near the surface given by: 1 m s^{-1} $< u_2 <$ 7 m s^{-1}	Beaufort Force 1 to 3

ensure a minimum level of ventilation, but not so great that sensors using radioactive probes will not be able to operate or that blowing snow is generated. If all three requirements are met, there will be a good likelihood that the conditions are those in which local disturbing factors will have been minimised.

These requirements lend themselves to automatic measurement systems, although the measurements available at some sites may not directly map on to the requirements identified. For example, cloud type and amount can be determined from solar radiation measurements, based on the fraction of diffuse radiation received at the surface (Harrison et al., 2008). Present Weather sensors may also report information relevant to each of the requirements listed, such as in identifying precipitation. The right-most column of Table 2 provides equivalent manual observations, for use at a site, currently or retrospectively where automatic meteorological measurements are not available.

5. Conclusions

Increasing interest in the global atmospheric electric circuit and the availability of electric field mill sensors has led to a global renaissance in measurements of the atmospheric electric potential gradient. For these measurements to be useful geophysically however, data selection is required to remove local effects. Meteorological criteria can be used to identify what has conventionally been known as fair weather atmospheric electricity data. Appropriate data selection, based on fair weather criteria provides both efficient use of the original measurements, and reduces the amount of averaging needed to overcome effects of random measurement fluctuations.

The three fair weather requirements described and refined here are: (FW1) the absence of hydrometeors, aerosol and haze, (FW2) negligible cumuliform cloud present and no extensive stratus cloud with its cloud base below 1500 m and (FW3) surface wind speed between 1 m s^{-1} and 8 m s^{-1}. The effects of aerosol and haze are particularly important to exclude, which can be achieved without sophisticated additional instrumentation by ensuring that the visual range exceeds 2 km. These three requirements are readily implemented at both automatic and manual sites. For sites such as geomagnetic observatories where no long-term meteorological data is available, fair weather requirements may alternatively be identified through the use of meteorological reanalysis data. (Reanalysis data provides a description of the local meteorological conditions from all the measured and model information available.) This work in refining the fair weather selection criteria therefore underpins the contemporary resurgence in atmospheric electricity measurements, and brings the additional benefit of demonstrating how archived historical atmospheric electricity data can be used for long term studies of the global circuit.

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Appendix. Standardisation of Potential Gradient measurements

In atmospheric electricity, the Potential Gradient measured at the surface is considered to be the difference between the potential of a point at a fixed distance above the surface which has obtained the local air potential, and the potential of the surface itself. The sensor which obtains the local potential is known as a potential equaliser or collector. The sensor's potential is measured with a voltmeter of very large input impedance, in order that a negligible current flows. This is shown conceptually in Fig. A1. In modern practice the measurement may be obtained using a field mill, which can be regarded as combining the sensor and voltmeter in a single device, with a datalogger.

If it can be assumed that negligible distortion of the lines of equipotential occurs due to the presence of the instrumentation, the PG at a height z, F_z is given by

$$F_z = \frac{V_0}{z} \tag{A1}$$

In a real situation, the effect of a vertical pointing support mast is usually to increase the abundance of equipotential lines compared with an open surface, and therefore to increase the PG measured. There may also be screening effects of buildings or trees. To correct for this, an additional factor f is introduced into equation (A1) as

$$F_z = f\frac{V_0}{z} \tag{A2}$$

Since f acts to decrease the measured value, it is often known as the *reduction factor*. Obtaining the value of f for a particular installation is known as standardisation. (This is distinct from calibration of the sensor itself, which can be done in the laboratory). Standardisation essentially require an experiment in which the PG measurements are compared with undisturbed PG measurements nearby, or through imposing a known vertical electric field. As a mast supporting a sensor is typically at 2 m or 3 m above the surface, an impractically large pair of horizontal plates would be needed to generate an electric field for the direct experimental approach. For some simple geometries, the amount of distortion can, alternatively, be found by calculation.

In general, three experimental approaches are available to provide the undistorted measurement, the calibration pit method, the passive wire antenna method and the imposed field method. Fig. A2 (a) depicts the general problem of the distorted electrostatic environment from the presence of an earthed mast and outlines the calibration arrangements needed for the pit and passive wire methods. In the pit method (Fig. A2b), a hole is dug and a further identical sensor is immersed in the surface, until it is flush with the surface. Subject to the actual practical circumstances encountered, the distortion will be much reduced or even absent. Simultaneous measurements with the pair of sensors are made and the reduction factor to be applied calculated from the ratio of the measurements. In the passive wire method (Crozier, 1963; Harrison, 1997), a long horizontal wire is stretched between insulators supported by two short masts as shown in Fig. A2(c). If the wire is much longer than the height of the masts, there will be negligible distortion of the electric field and the potential measured can be assumed to be the absolute atmospheric potential at the same height. From knowledge of the height the potential gradient can be calculated. Ultra-high quality insulation or active insulation techniques such as guarding are needed for this method. The imposed field method (not illustrated), requires the field meter to have an insulated case or a case added, and the potential on it driven by a power supply. From the variation in the field meter output in response to the field generated, the instrument can be calibrated (Chubb, 2014).

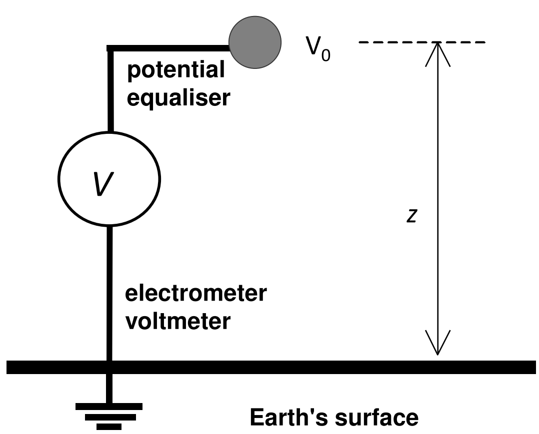

Fig. A1. Conceptual picture of the measurement of the vertical potential gradient (PG). A potential equaliser positioned at a height z comes into electrical equilibrium with the air around it, acquiring its potential V_0. The PG at height z is found as V_0/z.

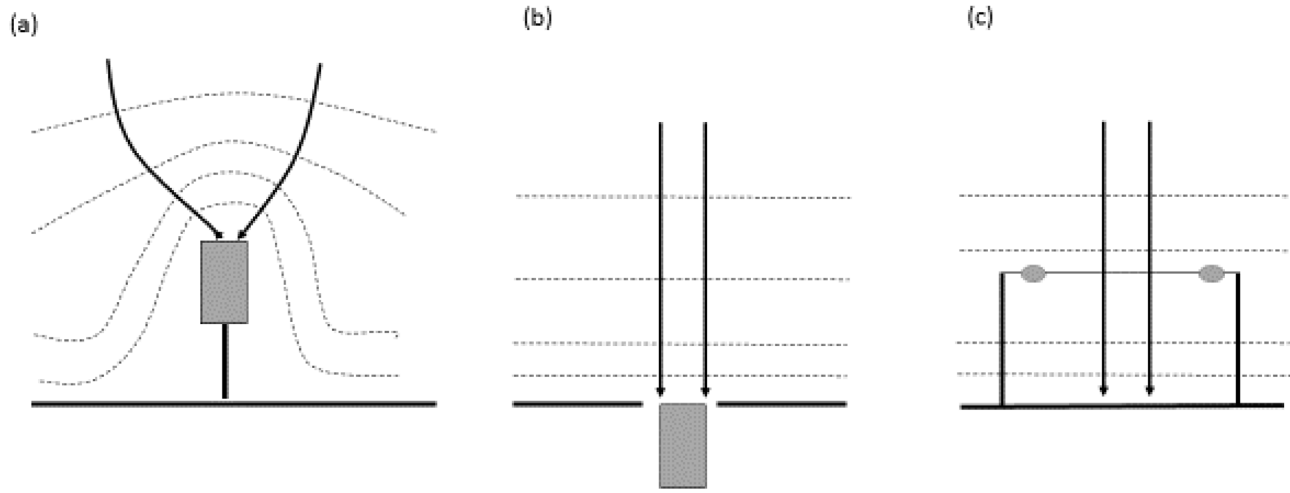

Fig. A2. (a) Effect of electric field distortion on a mast-mounted field meter. (b) Lessened effect of electric field line distortion by having the sensing surface of the field meter flush with the surface. (c) Use of a horizontal passive wire antenna to obtain the undistorted potential at a known height. (In each case, the dashed lines are equipotentials, and the solid lines are field lines).

References

Adlerman, E.J., Williams, E.R., 1996. Seasonal variation of the global electrical circuit. J. Geophys. Res. 101 (D23), 29679–29688.
Anisimov, S.V., Galichenko, S.V., Mareev, E.A., 2017. Electrodynamic properties and height of atmospheric convective boundary layer. Atmos. Res. 194, 119–129.
Anisimov, S.V., Galichenko, S.V., Aphinogenov, K.V., Prokhorchuk, A.A., 2018. Evaluation of the atmospheric boundary-layer electrical variability. Boundary-Layer Meteorol. 167, 327–348.
Aplin, K.L., 2012. Smoke emissions from industrial western Scotland in 1859 inferred from Lord Kelvin's atmospheric electricity measurements. Atmos. Environ. 50, 373–376. https://doi.org/10.1016/j.atmosenv.2011.12.053.
Aplin, K.L., Harrison, R.G., 2013. Lord Kelvin's atmospheric electricity measurements. Hist. Geo. Space Sci. 4 (2), 83–95.
Burns, G.B., Hesse, M.H., Parcell, S.K., Malachowski, S., Cole, K.D., 1995. The geoelectric field at Davis station, Antarctica. J. Atmos. Terr. Phys. 57 (14), 1783–1797.
Burns, G.B., Frank-Kamenetsky, A.V., Troshichev, O.A., Bering, E.A., Reddell, B.D., 2005. Interannual consistency of bi-monthly differences in diurnal variations of the ground-level, vertical electric field. J. Geophys. Res.: Atmosphere 110 (D10).
Burns, G.B., Tinsley, B.A., Frank-Kamenetsky, A.V., Troshichev, O.A., French, W.J.R., Klekociuk, A.R., 2012. Monthly diurnal global atmospheric circuit estimates derived from Vostok electric field measurements adjusted for local meteorological and solar wind influences. J. Atmos. Sci. 69 (6), 2061–2082.
Burns, G.B., Frank-Kamenetsky, A.V., Tinsley, B.A., French, W.J.R., Grigioni, P., Camporeale, G., Bering, E.A., 2017. Atmospheric global circuit variations from vostok and concordia electric field measurements. J. Atmos. Sci. 74, 783–800. https://doi.org/10.1175/JAS-D-16-0159.1.
Chalmers, J.A., 1967. Atmospheric Electricity, second ed. Pergamon press, Oxford, UK.
Chubb, J.C., 2014. The measurement of atmospheric electric fields using pole mounted electrostatic fieldmeters. J. Electrost. 72 (4), 295–300.
Corney, R.C., Burns, G.B., Michael, K., Frank-Kamenetsky, A.V., Troshichev, O.A., Bering, E.A., Papitashvili, V.O., Breed, A.M., Duldig, M.L., 2003. The influence of polar-cap convection on the geoelectric field at Vostok, Antarctica. J. Atmos. Sol. Terr. Phys. 65 (3), 345–354.
Crozier, W.D., 1963. Measuring atmospheric potential with passive antennas. J. Geophys. Res. 68 (18), 5173–5179.
Deshpande, C.G., Kamra, A.K., 2001. Diurnal variations of the atmospheric electric field and conductivity at Maitri, Antarctica. J. Geophys. Res. Atmospheres 106 (D13), 14207–14218.
Elhalel, G., Yair, Y., Nicoll, K., Price, C., Reuveni, Y., Harrison, R.G., 2014. Influence of short-term solar disturbances on the fair weather conduction current. J. Space. Weather. Space Clim 4, A26.
Everett, J.D., 1868. Results of observations of atmospheric electricity at Kew observatory, and at kings college, windsor, nova scotia. Phil. Trans. Roy. Soc. Lond. 158, 347–361.
Frank-Kamenetsky, A.V., Burns, G.B., Troshichev, O.A., Papitashvili, V.O., Bering, E.A., French, W.J.R., 1999. The geoelectric field at Vostok, Antarctica: its relation to the interplanetary magnetic field and the cross polar cap potential difference. J. Atmos. Sol. Terr. Phys. 61 (18), 1347–1356.
Hamilton, R.A., 1965. Secular and other changes of atmospheric electrical potential gradient at Lerwick. Q. J. R. Meteorol. Soc. 91, 348–352.
Harrison, R.G., 1997. An antenna electrometer system for atmospheric electrical measurements. Rev. Sci. Instrum. 68 (3), 1599–1603.
Harrison, R.G., 2003. Twentieth-century atmospheric electrical measurements at the observatories of Kew, Eskdalemuir and Lerwick. Weather 58 11–1.
Harrison, R.G., 2006. Urban smoke concentrations at Kew, London, 1898-2004. Atmos. Environ. 40 (18), 3327–3332.
Harrison, R.G., 2012. Aerosol-induced correlation between visibility and atmospheric electricity. J. Aerosol Sci. 52, 121–126.
Harrison, R.G., 2013. The Carnegie curve. Surv. Geophys. 34 (2), 209–232.
Harrison, R.G., Aplin, K.L., 2002. Mid-nineteenth century smoke concentrations near London. Atmos. Environ. 36 (25), 4037–4043.
Harrison, R.G., Aplin, K.L., 2003. Nineteenth century Parisian smoke variations inferred from Eiffel Tower atmospheric electrical observations. Atmos. Environ. 37, 5319–5324.
Harrison, R.G., Carslaw, K.S., 2003. Ion-aerosol-cloud processes in the lower atmosphere. Rev. Geophys. 41, 1.
Harrison, R.G., Märcz, F., 2007. Heliospheric timescale identified in surface atmospheric electricity. Geophys. Res. Lett. 34, L23816.
Harrison, R.G., Nicoll, K.A., 2008. Air-earth current density measurements at Lerwick; Implications for seasonality in the global electric circuit. Atmos. Res. 89 (1–2), 181–193.
Harrison, R.G., Chalmers, N., Hogan, R.J., 2008. Retrospective cloud determinations from surface solar radiation measurements. Atmos. Res. 90, 54–62.
Harrison, R.G., Joshi, M., Pascoe, K., 2011. Inferring Convective Responses to El Niño with Atmospheric Electricity Measurements at Shetland Environ Res Lett, vol. 6 044028.
Harrison, R.G., Nicoll, K.A., Aplin, K.L., 2017. Evaluating stratiform cloud base charge remotely. Geophys. Res. Lett. 44. https://doi.org/10.1002/2017GL073128.
Imyanitov, I.M., Shifrin, K.S., 1962. Present state of research on atmospheric electricity. Sov. Phys. Usp. 5, 292–322. https://doi.org/10.1070/PU1962v005n02ABEH003413.
Israël, H., 1970. Atmospheric Electricity. (2 Volumes), Israel Program for Scientific Translations, Jerusalem.
Markson, R., 2007. The Global Circuit Intensity: its Measurement and Variation over the Last 50 Years. Bulletin of the American Meteorological Society Feb 2007. https://doi.org/10.1175/BAMS-88-2-223.
Märcz, F., 1997. Short-term changes in atmospheric electricity associated with Forbush decreases. J. Atmos. Sol. Terr. Phys. 59 (9), 975–982.
Minamoto, Y., Kadokura, A., 2011. Extracting fair-weather data from atmospheric electric field observations at Syowa station, Antarctica. Polar Science 5, 313–318.
Nicoll, K.A., 2012. Measurements of atmospheric electricity aloft. Surv. Geophys. 33 (5), 991–1057.
Nicoll, K.A., Harrison, R.G., 2009. Vertical current flow through extensive layer clouds. J. Atmos. Sol. Terr. Phys. 71, 2040–2046.
Nicoll, K.A., Harrison, R.G., 2016. Stratiform cloud electrification: comparison of theory with multiple in-cloud measurements. Q. J. R. Meteorol. Soc. 142 (700), 2679–2691.
Odzimek, A., 2018. Personal Communication OYB Observatories' Year Book, Annual Volumes for 1964. Meteorological Office, HMSO, London, UK.
OYB, 1922–1967. The Observatories Year Book, Annual Volumes for 1922–1967. Meteorological Office, HMSO, London, UK.
Pierce, E.T., 1972. Radioactive fallout and secular effects in atmospheric electricity. J. Geophys. Res. 77, 482–487. https://doi.org/10.1029/JC077i003p00482.
Rycroft, M.J., Israelsson, S., Price, C., 2000. The global atmospheric electric circuit, solar activity and climate change. J. Atmos. Solar-Terr. Phys. 62, 1563–1576.
Rycroft, M.J., Nicoll, K.A., Aplin, K.L., Harrison, R.G., 2012. Recent advances in global electric circuit coupling between the space environment and the troposphere. J. Atmos. Sol. Terr. Phys. 90–91, 198–211.
Siingh, D., Singh, R.P., Gopalakrishnan, V., Selvaraj, C., Panneerselvam, C., 2013. Fair-weather atmospheric electricity study at Maitri (Antarctica). Earth Planets Space 65, 1541. https://doi.org/10.5047/eps.2013.09.011.

Takeda, M., Yamauchi, M., Makino, M., Owada, T., 2011. Initial effect of the Fukushima accident on atmospheric electricity. Geophys. Res. Lett. 38, L15811. https://doi.org/10.1029/2011GL048511.
Tinsley, B.A., 2008. The global atmospheric electric circuit and its effects on cloud microphysics. Rep. Prog. Phys. 71, 066801.
Tuma, J., 1899. Beiträge zur Kenntniss der atmosphärischen Elektricität III. Sitz. Ak. Wiss, Wien.
Wilson, C.T.R., 1929. Some thundercloud problems. J. Franklin Inst. 208, 1–12.
Yaniv, R., Yair, Y., Price, C., Katz, S., 2016. Local and global impacts on the fair-weather electric field in Israel. Atmos. Res. 172, 119–125.
Zhou, L., Tinsley, B.A., 2007. Production of space charge at the boundaries of layer clouds. J. Geophys. Res.: Atmosphere 112 (D11).