Variability in surface atmospheric electric field measurements

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Abstract. An electrical current of the order one picoamp per metre squared flows vertically in the Earth's atmosphere, between the ionosphere at approximately 50km altitude and the surface. This current is generated by global thunderstorm activity and is modulated by galactic cosmic rays and atmospheric aerosol. In fair weather conditions, this current cause a vertical atmospheric electric field, commonly measured as a potential gradient. For circumstances other than fair weather conditions, the potential gradient varies, from small steady enhancements in fog to large fluctuations in thunderstorms. The atmospheric potential gradient is continuously monitored at the Reading University Atmospheric Observatory. An account of the variability of the potential gradient on a variety of time scales will be presented.

1. Introduction
Global thunderstorms and shower clouds separate electric charge in the atmosphere, which maintains an electric potential difference of around $3 \times 10^5$ V between the surface and an altitude of approximately 50km, in the lower ionosphere. The atmosphere is weakly electrically conductive due to ionization from galactic cosmic rays and, near the surface, terrestrial radioactive sources. Ion generation is balanced by the loss of ions from ion-ion recombination, or attachment to aerosol particles; the latter is the dominant process in the lower troposphere. This steady-state concentration of atmospheric ions along with the surface-ionospheric potential difference permits a vertical conduction current density of order $1 \times 10^{-12}$ Am⁻² to flow in all fair-weather regions around the globe, completing the global atmospheric electric circuit. The global circuit concept was originally proposed by the Nobel Prize winner C.T.R. Wilson¹.

A schematic of the global circuit is given in Figure 1. The fair weather conduction current flowing through the resistive atmosphere generates a vertical electric field (known as the potential difference, PG, which is in fact the negative of electric field by convention). The magnitude of this fair-weather conduction current density is independent of height under steady-state conditions, so it is the variation of air conductivity with height that determines the PG vertical profile. When this current flows through the particularly low conductivity air ($\sim 10^{-14}$ S/m) found near the surface, which arises from a low cosmic ray ion production (ion source term) and high aerosol concentration (ion loss term), a relatively large potential gradient ($\sim 100$ V/m) develops in accordance with Ohm’s Law. The PG produced by the vertical current flow through the air that is defined here as the fair-weather PG. This fair-weather PG

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is continuously present in our atmosphere, since it is a function of the current in the global circuit, which is in turn continuously generated by global thunderstorm activity.

Variability of this fair-weather PG due to the conduction current density will occur on the timescale equal or exceeding that of the electrical relaxation time constant of the atmosphere near the surface, at between 5-40 minutes, depending on the air conductivity\(^2\). However, the magnitude of variability due to the global circuit is likely to be relatively low compared to other sources, with a characteristic diurnal variation of about 20% of the mean PG. Seasonal cycles in the global circuit are also likely in accordance to global thunderstorm and shower cloud seasonality\(^3\), although this is still the subject of ongoing research. In addition to variability in the global circuit, electrically charged pockets of air (space charge) transported by turbulent eddies will cause small (order 10V/m) deviations from the mean PG, but of a higher frequency to that attributed to global variation, on the timescale of seconds to minutes, depending on the turbulent processes involved.

The largest source of variability in surface PG by far is that generated by meteorological processes, in particular the electrostatic fields associated with charged regions within clouds passing above the observation site. In particular, during times of disturbed weather with the presence of convective clouds (shower clouds and thunderstorms) and associated precipitation can cause short-period (order minutes to hours) variations many times the mean value of fair-weather PG, and of both signs. In these circumstances, nearly all global signals evident in the surface (fair-weather) PG are masked, with variability under disturbed weather attributed to local effects.

Any process by which the conductivity of the air is changed will change the PG for a fixed conduction current. The usual cause of a conductivity change near the surface is due to a change in aerosol concentration. This can either be increased air pollution (anthropogenic sources, dust etc.) or condensation of water droplets as mist or fog, both of which remove the small ions by attachment, effectively removing them from the electrical system owing to their independence of motion to the local PG (and will instead become space charge, transported by turbulent, not electrostatic processes). It is not surprising therefore that air conductivity can be used used effectively as an indicator of historical aerosol concentration over urban areas\(^4\). A removal of ions by aerosol attachment decreases air conductivity and increases the PG by Ohm’s Law. The magnitude of this variability due to aerosol depends on the change in aerosol concentration involved, but there is typically 100V/m increase in
fog, reaching approximately 600V/m increase in dense fog. Timescales of this variability will also naturally depend on the timescale of the aerosol event, ranging from the relaxation time of the near-surface air (5-40min) to seasonal timescales and beyond.

2. Measurement of Potential Gradient
The PG has been continuously measured at the Reading University Atmospheric Observatory (RUAO) since April 2005. A commercially available electrostatic field mill (JCI 131) mounted on a 2m pole is used to record the PG, providing measurements at less than 1V/m resolution under all meteorological conditions. The principle of operation is through charge induced on rotating metallic blades as they are alternately shielded and exposed to the ambient PG through sections cut from a metallic aperture at the top of the instrument. The induced charge is proportional to the PG and this method is able to produce high frequency (order 100Hz) sampling.

The electrostatic field mill has been calibrated using a horizontal long wire passive antenna, fixed at a height of 1m. The antenna records the potential 1m above the ground, and thereby the mean PG between the surface and 1m\(^3\). As such, the observations are of the vertical PG calibrated to 1m above the surface (although technically the calibration is for the mean PG between the surface and 1m, variation of PG in this range is considered small). Measurements at the RUAO are made every second and five minute mean values calculated.

3. Observation of potential gradient variation
Variation of the PG occurs over a broad range of timescales, from the high frequency response of turbulent space charge and precipitation, the passage of charged clouds, the diurnal variation of global thunderstorm activity and aerosol vertical profile, through to the seasonal variation of near-surface aerosol concentration, global thunderstorm activity and even decadal variation in galactic cosmic ray intensity\(^6\). As such, observation of the variation of PG has been split into two sections, the former identifying sub-diurnal trends, and the latter referring to longer timescales.

3.1. Sub-diurnal variation
A histogram of the hourly mean PG recorded at the RUAO is given in Figure 2. From this plot it can be seen that, for the majority of time, the hourly mean PG is between 80 and 160V/m, with an overall mean of 107V/m, characteristic of fair-weather, and standard deviation of 83V/m. The tails of the distribution indicate that there are times when the PG is 2 or 3 times away from this standard deviation, including a negative hourly mean PG. Variation of this magnitude occurs during times of disturbed weather, when charged regions (of both signs) within passing clouds cause marked deviations of PG from the mean, commonly causing a complete reversal of PG to negative values during disturbed weather such as moderate rainfall, making the distribution of hourly mean PG negatively skewed.

The effect of disturbed weather in causing large variation of the PG can also be seen in Figure 3 where there is evidence of a pronounced positive skew to the standard deviation of five minute mean PG calculated at hourly intervals. This histogram of standard deviation continues to over 1000V/m but is limited here to only 150V/m for display purposes, owing to the small frequency of occurrence of such extreme events. As such, it can be seen that even in the absence of disturbed weather, the five minute mean PG is still constantly changing, with typical deviations of 20-40V/m over an hour. The large standard deviation during days with disturbed weather is also seen in Figure 4, showing the standard deviation of five minute mean PG at daily intervals between 1 May 2005 and 1 November 2006. The daily standard deviations approaching 500V/m indicate days of highly disturbed weather such as thunderstorms or heavy showers. Occurrences of such days are during the two summers sampled here, where heavy showers and thunderstorms are more frequent than during the winter time.
Figure 2. Histogram of hourly mean PG recorded at the RUAO between 1 May 2005 and 1 November 2006.

Figure 3. Histogram of standard deviation of five minute means of PG at hourly intervals, recorded at the RUAO between 1 May 2005 and 1 November 2006.

Figure 4. Standard deviation of five minute mean PG at daily intervals with date, recorded at the RUAO between 1 May 2005 and 1 November 2006.
3.2. Daily and seasonal variation

Daily and seasonal variability is evident from the daily mean PG plotted with date in Figure 5. The daily mean PG has a standard deviation of 49 V/m in this dataset, slightly over half that of the five minute means at hourly intervals, suggesting that there is still considerable variability with periods greater than a day. The main source of this day-to-day variability in PG is cloud and precipitation (as previously discussed, both are charged, so will alter the PG), which is known to have variability on these timescales. It is of note that there are negative values of daily mean PG, which would occur if the day had persistent disturbed weather, usually in the form of prolonged and moderate rainfall.

Superimposed on this daily variability is evidence for a seasonal trend in daily mean PG, with higher mean values in the winter and lower in the summer. The reason for this season variability is likely to be due to increased aerosol concentration near the surface during winter than summer, as the lack of strong surface heating and deep convective mixing means that the pollution generated at the surface is confined to the near-surface where the PG is measured and not distributed upwards by summertime convective mixing. Additionally, the relative humidity of air near the surface is generally higher in winter, prompting more fog events and aerosol swelling (haze), both of which lowers the air conductivity and increases the PG. Seasonality attributed to the global circuit via seasonal variation in global thunderstorm activity is also likely, but any influence attributed to this are not yet fully understood.

Figure 5. Daily mean PG with date recorded at the RUAO between 1 May 2005 and 1 November 2006, showing the wintertime increase in PG due to higher aerosol concentration at the surface.
4. Conclusion

PG at the RUAO between 1 May 2005 and 1 November 2006 has variability on all measured timescales, with influences from both local and global effects. The greatest variability is due to the passage of charged regions within clouds. During fair-weather with no clouds present, the PG is still variable at the short timescales due to the turbulent transport of space charge and fluctuations of the conduction current that generates the fair-weather PG (in particular, the diurnal variation of global thunderstorm activity causes a variation of ~ 20%). Air conductivity changes resulting from a change in aerosol concentration are also observed at varying timescales (including seasonal), although the variability attributed to these effects is considerably lower than that arising from charged clouds.

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