Surface atmospheric electrical responses to solar energetic particles at mid-latitudes

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ABSTRACT: Solar energetic particles (SEP) can occasionally contribute additional atmospheric ionisation beyond that arising from the usual galactic cosmic ray (GCR) background. Such enhancements in ionisation can penetrate down to the troposphere, and in extreme cases, reach the surface, perturbing atmospheric electric parameters through changes in the vertical conductivity profile. This work presents evidence of enhanced atmospheric ionisation at mid-latitudes measured by a balloon borne sensor, down to an altitude of 10km due an SEP event originating from a solar flare on 11th April 2013. Simultaneously with the same SEP event, substantial fluctuations were also observed in potential gradient and vertical conduction current measurements at Reading. As no coincident changes in geomagnetism occurred, the electrical fluctuations can be attributed to increased ionisation from the energetic solar particles. The large (up to 220V/m change in PG) and transient nature of the electrical changes suggests that episodic ionisation generation and/or charge accumulation occurred, with electrostatic induction, rather than conduction being responsible for the observed changes. Since no increase in ionisation was detected by the global network of surface neutron monitors, this suggests that there are moderately energetic solar particles which have electrical effects within the troposphere, but remain undetected in surface neutron monitors. Our experimental approach illustrates that such space weather effects on lower atmosphere ionisation could nevertheless be regularly and effectively observed using modified meteorological radiosondes.

INTRODUCTION

Earth's electrical environment is influenced by internal drivers (including the global charging current from thunderstorms which is dependent on the number and strength of thunderstorm; global aerosol concentrations and cloud cover), as well as external drivers. The external influences result from a variety of different space weather phenomenon including variations in the solar magnetic field, geomagnetic field variations and ionisation changes from Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs). Understanding the mechanisms by which external influences affect atmospheric electrical parameters is difficult as most space weather events are a complicated superposition of several different effects. For instance, although a number of atmospheric electrical responses to short term solar events have been reported in the literature (e.g. Cobb (1967), Holzworth and Mozer (1979), Kasatkina et as (2009)), almost all report measurements during periods when enhanced geomagnetic variability accompanies enhanced ionisation, and hence the results of magnetic or ionisation influences are difficult to separate. The observations presented here occurred during a Solar Energetic Particle (SEP) event, in which only changes in proton flux were observed, with no significant variations in geomagnetic field. Thus this event presents a rare opportunity to investigate the particle related effect on atmospheric electrical parameters during short term solar disturbances.

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During energetic solar events such as solar flares, large numbers of Solar Energetic Particles (SEPs, mostly protons) can enter Earth's atmosphere, with the geomagnetic latitude and altitude they can penetrate down to depending on their energy. Most primary protons of energy less than 500MeV are absorbed above 15km, however primary protons of energy > 500MeV will generate a cascade of secondary particles through interactions with atmospheric molecules, producing enhanced ionisation rates above that of the normal background rate from Galactic Cosmic Rays (Bazilevskaya, 2005). On rare occasions, when the primary SEPS have energies ≈GeV, the secondaries can be of sufficient energy to reach ground level, causing a Ground Level Event (GLE).

The effects of SEP events on atmospheric electrical variables can be seen directly from the balloon measurements of Kokorowski et al (2006) and Holzworth et al (1987), demonstrating that effects on atmospheric electrical parameters (through an increase in the electrical conductivity resulting from enhanced ionisation from the SEPs) can be appreciable at high altitudes and at high latitudes, although the influence of SEPs on global atmospheric current flow are thought to be much smaller (Holzworth and Mozer, 1979; Reagan et al, 1983). This paper presents evidence of enhanced ionisation rates down to tropospheric altitudes at mid-latitudes during an SEP event on 11th April 2013 from a new balloon borne ionisation sensor. During this event, substantial fluctuations were detected in surface measurements of atmospheric electrical parameters beneath the balloon, but no GLE was detected by surface neutron monitors. The measurements presented here not only demonstrate increased ionisation down into the troposphere, but also an influence of energetic particles on atmospheric electrical parameters at mid latitudes during a relatively small SEP event.

OBSERVATIONS OF ATMOSPHERIC IONISATION

The solar proton event originated from an M6/3b solar flare on 11th April 2013, with a peak in the X-ray flux detected at 0716UT. Enhancement of the >100MeV proton flux began at 0940UT and the 10MeV flux at 1055UT (using the criteria defined for GOES SEP event alerts). There was no discernible perturbation of the geomagnetic field by the flare, supported by a planetary Kp index value of <2 throughout 11th and 12th April 2013. The >2 MeV electron flux at geosynchronous orbit was also at normal to moderate levels throughout the period of interest.

Vertical profiles of ionisation during the SEP event were made from a mid latitude site at Reading, UK (51.45°N, 0.97°W), using a pair of Geiger tube sensors (Harrison et al 2013) flown on a free balloon platform alongside a standard meteorological radiosonde. The "Geigersonde" measuring device uses a compact and efficient high tension supply for two miniature LND714 Geiger tubes. Data from the Geigersonde was returned to the surface in real time through a Vaisala RS92 radiosonde using a PANDORA interface (Harrison et al 2012), allowing transmission of the extra sensor data synchronous with the standard meteorological measurements of pressure, temperature, relative humidity and GPS position made by the radiosonde. Figure 1 shows the average ionisation profile above Reading during 2013 (in black), demonstrating the increase in ionisation with height until the Pfotzer maximum is reached at ~17km. Also shown in Figure 1 are ionisation measurements from two balloon flights performed during the SEP event; flight 1 (orange) from 1319 to 1449UT on 11th April, and flight 2 (purple) from 0931 to 1242 UT on 12th April. The Geiger count rates are enhanced during the SEP event on 11th April, throughout the altitudes from that of the maximum height reached (25km) down to ~10km, with a 26% increase in the ionisation rate at 20km above normal background levels. It is also interesting to note that, although the Geigersonde count rate is elevated during the flight on 11th April, on the 12th April the count rate lies within the undisturbed range, despite the sustained enhanced proton flux measured at GOES for the same period. The observations represent a transient response in the atmospheric ionisation, and/or that the energies detected by the Geigersonde on 11th April were those of higher energy particles, which were no longer sufficiently enhanced to be detected against the typical variability.

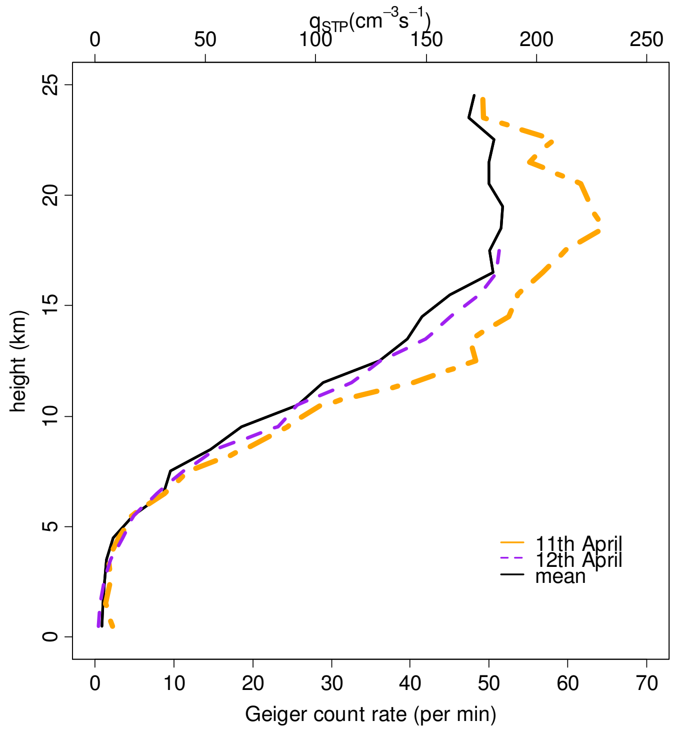

Figure 1. Vertical profiles of ionisation rate measured over Reading, UK from a balloon borne Geigersonde. The mean profile from 3 undisturbed flights during 2013 is shown in black, during the SEP event on 11th April 2013 (orange, 1319 UT), and towards the end of the SEP event on 12th April 2013 (purple, 0931 UT).

An increase in the flux of ionising particles during the SEP event was also detected in the stratosphere by balloon measurements made by the Lebedev Physical Institute at polar latitudes. Measurements from Mirny, Antarctica, at 0300UT on 12th April using a Geigersonde of different design showed increased ionisation down to ~27km (Bazilevskaya, 2014). This supports the SEP event being capable of yielding increased atmospheric ionisation, such as that observed over Reading during the earlier phase of the same event at 1319UT on 11th April.

Despite observed increases in the ionisation rate at high altitudes, from several latitudes during the SEP event, no increase was detected by the network of surface neutron monitors. This is surprising since, given the relatively high geomagnetic cutoff rigidity of Reading (geomagnetic latitude ~ 47.5°N), the primary particles responsible for the increased ionisation over Reading would need to be of energy of at least 2 GeV. Such particles would generate a cascade of secondary particles, including neutrons, detectable by surface neutron monitors. The fact that no increase in neutron counts was detected suggests that the neutrons were not of sufficient number or energy to trigger the surface neutron monitors (which may be related to the angular distribution of the incoming primary particles). Further, neutron monitors are primarily sensitive to the hadronic (i.e. nucleonic) component of the secondary cascade of energetic particles, whereas the Geigersonde tubes are mostly sensitive to the muon component; this difference in the measurement technology (including a higher sensitivity of the Geigersonde to low energy particles than neutron monitors) may account for some of the discrepancy between the balloon and neutron monitor measurements. The typical number of GLEs recorded by neutron monitors during a solar cycle (around 12-15) is much less than the number of SEPs recorded from balloon measurements (22-23) (Bazilevskya, 2005). Hence the observations on 11th April 2013 may well represent another SEP event undetected by surface neutron monitors.

SURFACE ATMOSPHERIC ELECTRICAL MEASUREMENTS

Figure 2 (a) shows a time series of the X-ray flux and rate of change of high energy proton flux measured by the GOES13 satellite during the flare emission period and corresponding SEP event. Also shown are measurements of surface atmospheric electrical parameters measured at Reading University Atmospheric Observatory (RUAO) between 0600 and 1100UT on 11th April, during the period of the SEP event, from which the Figure 1 balloon profiles were made. The surface measurements were sampled at 1 Hz. Potential gradient (Figure 2(b)) is measured using a Chubb JCI 131 electric field mill, set on a 0-2 kV/m range. It points vertically upward with its sensing aperture at a height of 3m above the surface. The vertical current flow (Figure 2(c)) is measured using the Geometrical Displacement and Conduction Current Sensor, GDACCS (Bennett and Harrison, 2008), using a horizontal plate electrode with a sensitive electrometer to measure the current flowing to the plate.

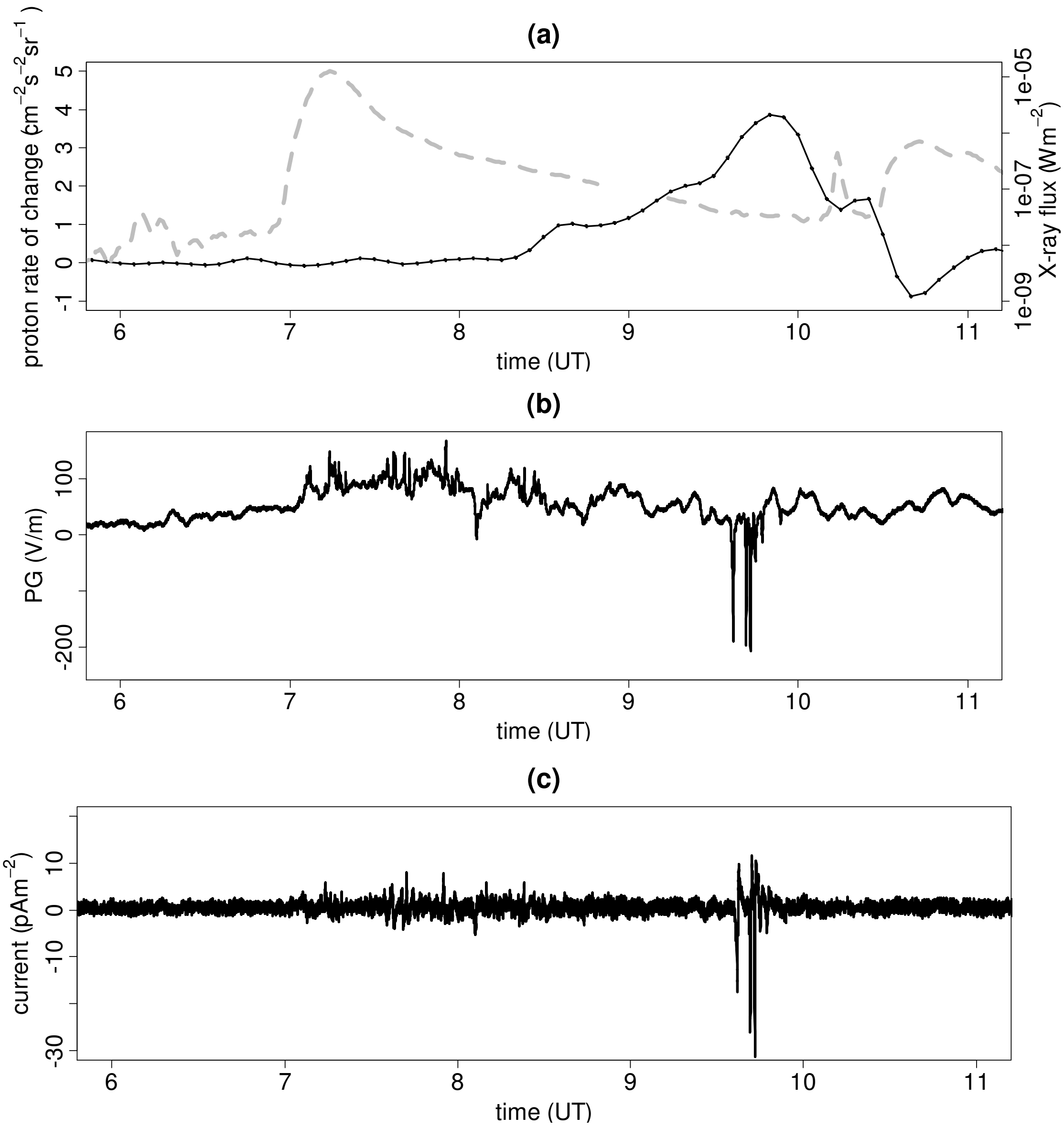

Figure 2. (a) Rate of change of >60MeV proton flux (black solid line) and X-ray flux (grey dashed line) from GOES 13, measured between 0600 and 1100 UT on 11th April 2013 during an SEP event. (b) Potential Gradient (PG) and (c) vertical conduction current measured at the University of Reading, UK during the same time period.

Figure 2 (b) and (c) demonstrate substantial changes occurred in the atmospheric electrical parameters at Reading during the period of the SEP event. The fluctuations in both electrical parameters occurred approximately 2 hours after the end of the flare period, coincident with the maximum in the rate of change of >60MeV protons. Since the maximum rate of change in the lower energy proton fluxes occurs later (0954UT and 1012UT for >30Mev and >10MeV protons respectively), this suggests that the atmospheric electrical responses are primarily a result of ionisation from the high energy tail of the SEP particles. The transient nature of the electrical fluctuations suggests that the proton cloud contained a distribution of particle velocities and energies, with extensive spatial structure (e.g. Mazur et al, 2000).

Figure 3 examines the atmospheric electrical changes apparent between 0930 and 1000 UT in more detail. It is seen that both the PG (Figure 3(a)) and vertical conduction current (Figure 3(b)) show a reduction over a period of about 15 seconds, followed by a gradual recovery to fair weather values in approximately 15-30 seconds (approximately 50Vm^{-1} for the PG and 1pA for the conduction current), during multiple periods. The changes in both PG and current are large (~220V/m change in PG and 20 pAm^{-2} in current), and negative, suggesting negative charge aloft.

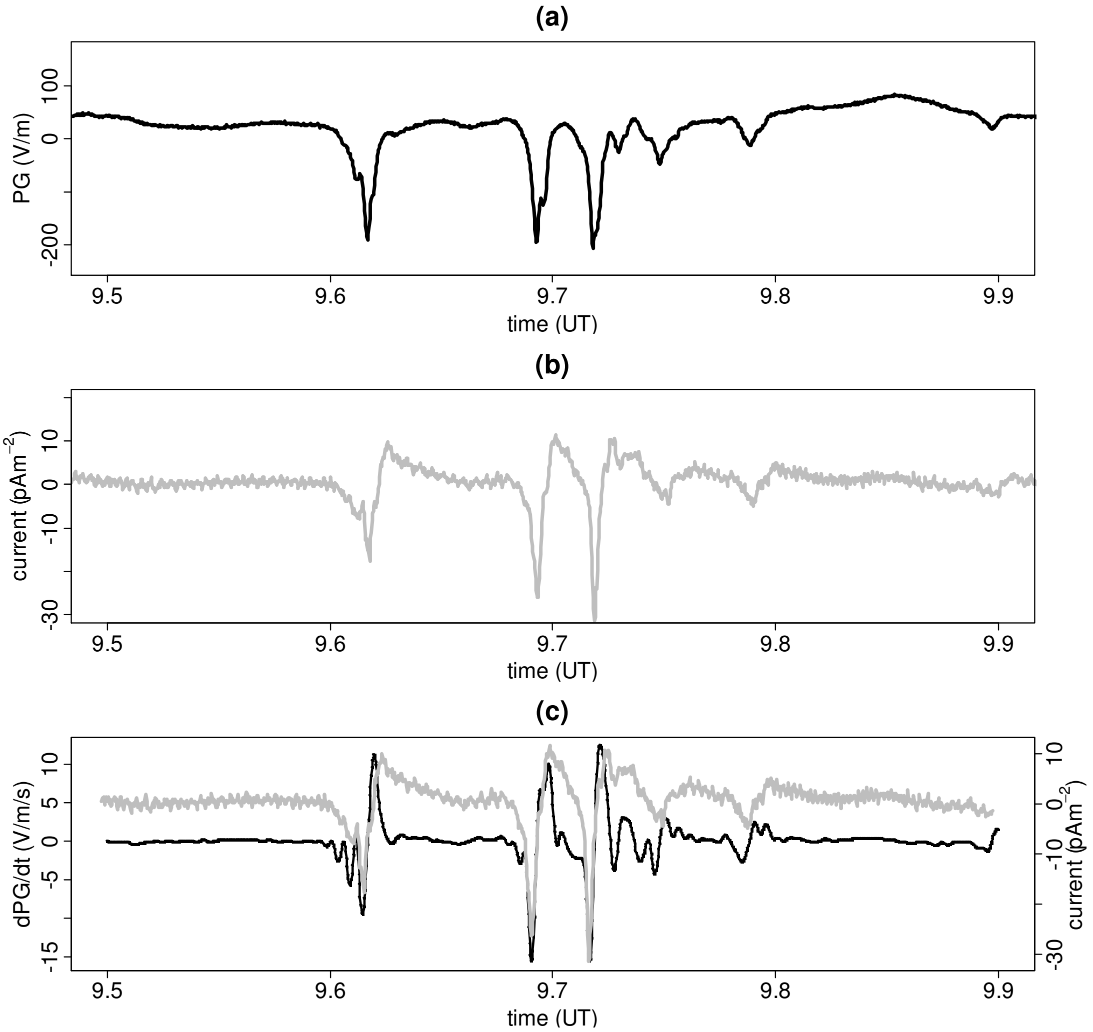

Figure 3. Atmospheric electrical parameters measured from Reading University Atmospheric Observatory (RUAO) on 11th April 2013 during an SEP event. (a) Potential Gradient (PG), (b) vertical conduction current, and (c) rate of change of PG (black) plotted alongside vertical conduction current (grey).

The large magnitude and transient nature of the electrical changes shown in Figure 3 suggests that electrostatic induction, rather than conduction was responsible for the observed changes. This would be consistent with transient changes in the charge distribution above Reading occurring as a result of the increased ionisation from high energy SEP particles, inducing displacement currents in the atmospheric electrical instruments beneath. This is supported by Figure 3(c) which shows the rate of change of PG with time, plotted alongside the conduction current measurements (corrected for a time lag from a smoothing capacitor on the output of the GDACCS). Since the displacement current is proportional to the rate of change of PG, the similarity between the two traces shown in Figure 3(c) supports the conclusion of the transient electrical changes resulting from induced displacement currents.

Atmospheric electrical parameters can be sensitive to changes in local weather conditions, particularly precipitation and wind, therefore it is necessary to consider whether the fluctuations observed could have arisen solely from variability in the local weather conditions. Figure 4 demonstrates that no significant changes in temperature, relative humidity, wind speed or wind direction or solar radiation occurred during the disturbed period considered (conditions were dry with overcast cloud, as is shown by the similarity between the global and diffuse radiation in Figure 4(b)). Further, no changes in rainfall were detected by three rain gauges at the site therefore the electrical variations could not be attributed to light rainfall. This analysis suggests that the fluctuations measured in atmospheric electrical parameters on 11th April 2013 were not due to local meteorological changes.

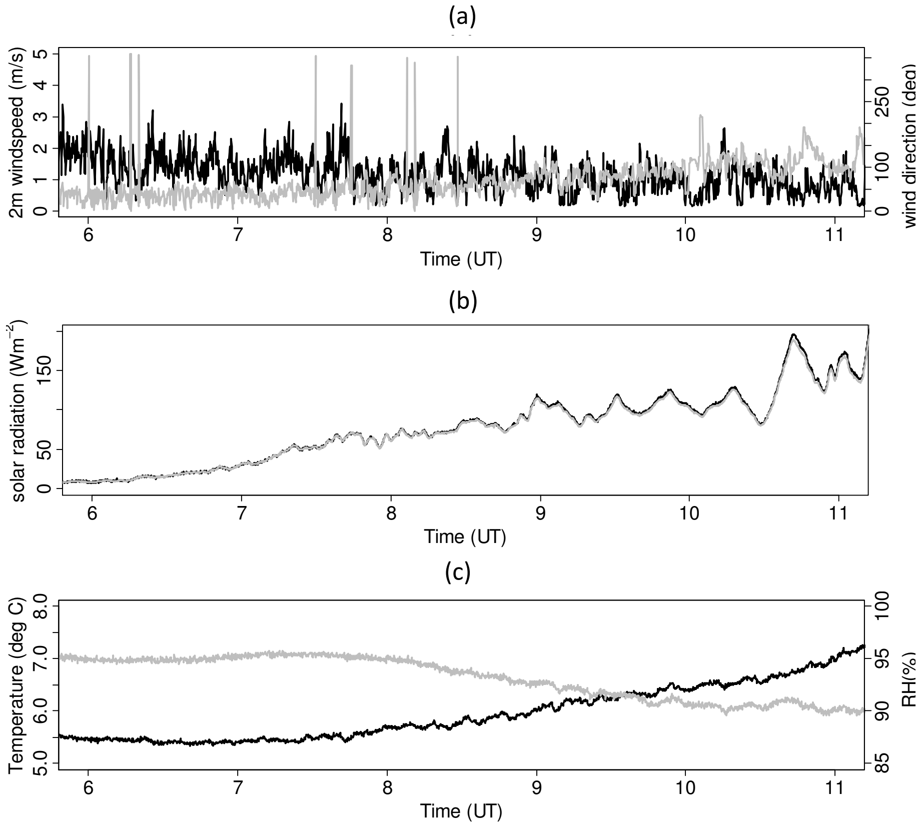

Figure 4. Weather conditions at RUAO during April 11th 2013 (10 second averages). (a) Wind speed measured at 2m (black line) and wind direction (grey line), (b) global solar radiation (black line) and diffuse solar radiation (grey line), (c) dry bulb temperature (black line) and relative humidity, RH (grey line).

CONCLUSIONS

This paper presents simultaneous measurements of increased ionisation in the troposphere from balloon measurements, with a response in surface atmospheric electrical parameters at mid-latitudes during an SEP event. This event was unusual in that no geomagnetic disturbances occurred simultaneously with the ionisation changes, enabling the atmospheric electrical changes to be attributed solely to ionisation effects. We suggest that the changes in electrical parameters resulted from increased ionisation from the high energy tail of SEP particles, present at the start of the event, which would act to enhance the conductivity in the column above the measurement site. The transient PG changes clearly evident in Figure 3(a) indicate episodic ionisation generation and/or charge accumulation. The large magnitude of the electrical changes suggests an electrostatic origin, which may arise, for example, from a large amount of charge being suddenly delivered into the atmosphere over a substantial horizontal region.

Although an increase in the flux of high energy particles was detected outside Earth's atmosphere by GOES satellite instruments, no detection of increased ground level ionisation was made by the worldwide neutron monitor network. This suggests that there are moderately energetic solar particles which have electrical effects within the troposphere, but remain undetected in surface neutron monitors, presumably due to the low flux of energetic particles. Although the neutron monitor data provides a proxy for atmospheric ionisation (Bazilevskaya et al, 2008) these findings therefore indicate that a gap exists in the current observational network of solar energetic particles. Hence the evaluation of the basic rate of influential solar energetic particle events may still neglect weak events causing atmospheric ionisation. Our experimental approach illustrates that such space weather effects on lower atmosphere ionisation could nevertheless be regularly and effectively observed using modified meteorological balloons.

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