Space weather influences on atmospheric electricity

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The atmospheric electrical environment

Atmospheric electricity is a venerable topic of geophysical science, dating back to the 1750s when Franklin and Dalibard established the presence of electricity in thunderstorms. Subsequently, even fine conditions were observed to be electrified, with a downward vertical atmospheric electric field of magnitude ~100Vm^{-1} observed near the surface during fair-weather conditions.[1] The origin of the 'fair-weather field' remained unknown during the pioneering electrical measurements of the geophysical survey ship *Carnegie* in the 1920s, which demonstrated a diurnal variation in the electric field aligned with universal time rather than local time. This characteristic variation remains known as the 'Carnegie Curve' and was subsequently demonstrated as similar to the diurnal variation in global thunderstorm area. This supported the idea of a 'global atmospheric electric circuit' (GEC), postulated by C. T. R. Wilson (Wilson, 1929; Harrison, 2011), through which charge separation in thunderstorms sustains large-scale current flow around the world and the fair-weather field, now confirmed by Blakeslee *et al*. (2014). Figure 1 shows the GEC, where the Earth's surface and the lower ionosphere (at approximately 60km altitude) are represented as two oppositely charged 'electrodes') of a spherical capacitor, within which air provides a leaky dielectric. Charge transfer from thunderclouds, rain and lightning continuously electrify the ionosphere to a potential 250kV more positive than Earth's surface, known as the ionospheric potential, V_i.

Atmospheric air is conductive due to the presence of cluster ions, which are created primarily from galactic cosmic rays (GCRs), highly energetic hydrogen or helium nuclei (~GeV energy) from outside our solar system, and also, near the surface, from Earth's natural radioactivity. As GCRs enter Earth's atmosphere, they create a cascade of ions through interactions with atmospheric molecules. The conductive nature of air means that the potential difference between the ionosphere and the Earth's surface is associated with a return current, known as the air–Earth conduction current density, J_c. This vertical current flows globally in fair-weather regions, between the ionosphere and the surface. In the vertical dimension, Ohms' law relates J_c to V_i and the total resistance of a unit-area column of air from the ionosphere to the surface, R_c, by

$$J_c = \frac{V_i}{R_c}. \qquad (1)$$

The columnar resistance, R_c, is related to the conductivity of the vertical atmospheric column, where $\sigma(z)$ is the air conductivity at altitude z. The R_c value is determined by integrating the resistance of atmospheric layers from the surface to the ionosphere, by evaluating

$$R_c = \int_0^\infty \frac{dz}{\sigma(z)}. \qquad (2)$$

The conductivity, σ, is directly proportional to the ionisation rate and, above the surface, depends principally on the GCR flux entering Earth's atmosphere. (This can be measured at the surface using a neutron monitor.[2])

Atmospheric electricity and space weather

Earth's electrical environment is influenced by external as well as internal drivers, including the global charging current from thunderstorms (dependent on the number and strength of thunderstorms, and ENSO), and global aerosol concentrations and cloud cover, which can increase R_c. The external influences (identified in red in Figure 1) form the remainder of this discussion, which 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 GCRS.[3] From Equations (1) and (2) it follows that a change in either σ or V_i will result in a change in the global conduction current J_c. To understand the various mechanisms by which space weather may influence atmospheric electricity, the following sections discuss space-weather effects on σ and V_i.

Conductivity changes

A variety of space-weather-related phenomena can modify the ionisation rate and therefore affect σ. The GCR flux arriving at Earth, which is responsible for most of the ionisation in Earth's atmosphere, is modulated by the geomagnetic field, as well as the solar magnetic field, which has an 11-year cycle but also varies transiently due to coronal mass ejections (CMEs) and solar flares. The solar magnetic field acts as a barrier to GCRs, therefore during a CME, stronger magnetic-field irregularities in the solar wind can cause enhanced scattering of incoming GCRs, causing a sudden decrease in the GCR flux at Earth, known as a Forbush decrease.

Free-balloon measurements by Gringel (1978) demonstrated how the conductivity decreased down to altitudes of 10km over Germany on 8 August 1972, following solar flares on 2, 4 and 7 August, corroborated by a decrease of 20% in the GCR flux measured by a neutron monitor at Oulu, Finland. Effects of Forbush decreases on surface atmospheric electrical parameters are also evident in a decrease in the electric field (e.g. in Hungary (of ~10Vm^{-1}; Märcz, 1997)), using a superposed epoch-analysis technique to combine multiple events.

During energetic solar events such as solar flares, large numbers of 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

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[1] Fair-weather conditions are those in which no local charge separation processes are occurring.

[2] Neutron monitors detect the secondary neutron component of the GCR particle cascade at the surface. There is currently a worldwide neutron-monitor network spanning a variety of geomagnetic latitudes.

[3] The term 'geomagnetic field' refers to Earth's magnetic field.

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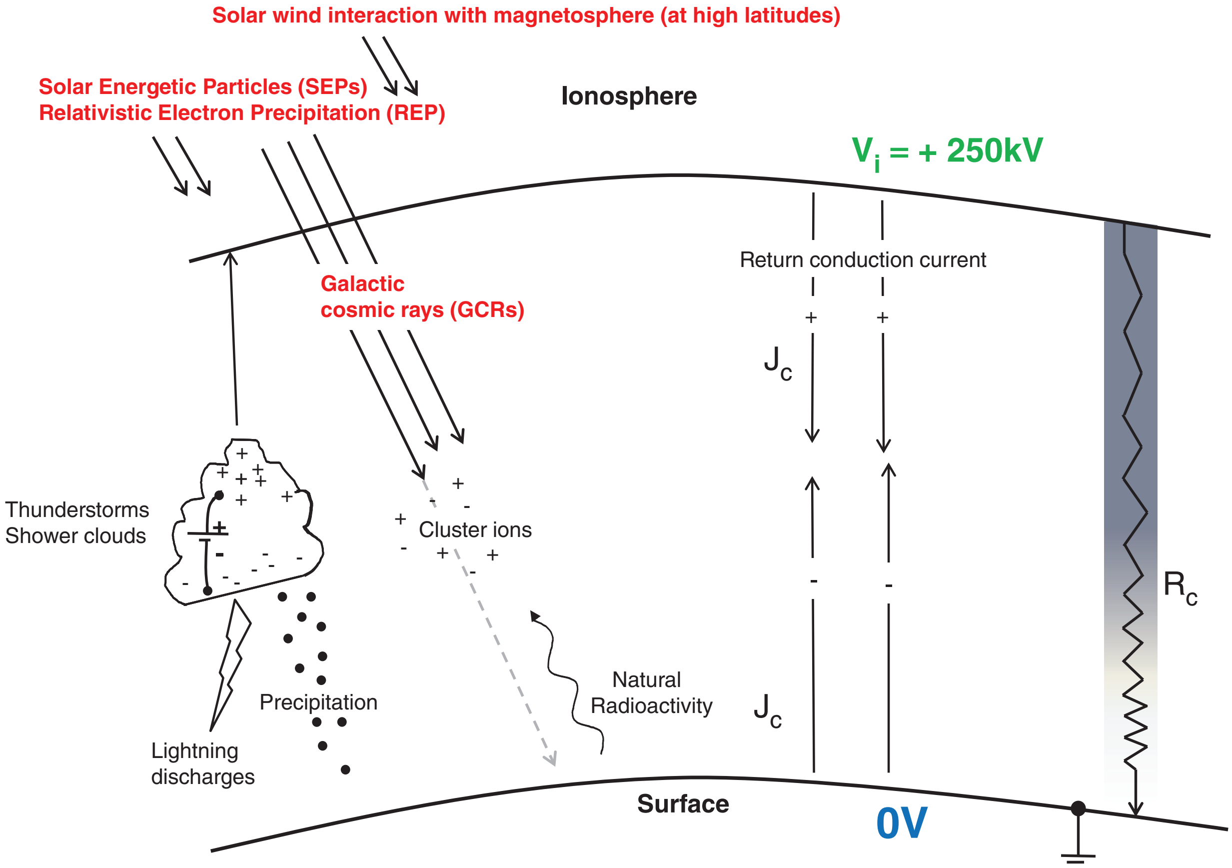

Figure 1. Atmospheric charge generation and transport, including important processes in the global electric circuit. Thunderstorms and electrified shower clouds act as batteries for the circuit, with the current carried by cluster ions, generated by radioactivity and galactic cosmic rays. J_c denotes the vertical conduction current density, R_c the columnar resistance, and the shaded bar characterises the change in potential with altitude, from a value of 0V at Earth's surface to +250kV in the ionosphere. Processes known to be related to space weather are depicted in red. (Adapted from Rycroft et al. (2012).)

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. 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). Relativistic electron precipitation (REP) (keV to MeV) provides an additional source of ionisation down to altitudes of ~50km, however, the associated X-ray Bremsstrahlung produces ionisation down to about 20km (Fram *et al*., 1997). Increases in ionisation rate from SEPs and REP are highly latitude dependent, as geomagnetism modulates particle penetration into the atmosphere, allowing greater particle flux at high latitudes from reduced geomagnetic shielding at the magnetic poles. Figure 2 demonstrates the normal ionisation profile measured in the atmosphere due to GCR ionisation (black line) and its enhancement for a hypothetical SEP event at different periods during the event (red and blue lines). Developments in technology mean that ionisation sensors can now be flown alongside standard meteorological radiosondes, as exemplified by the sensors developed at the University of Reading (Harrison *et al*., 2013a; inset Figure 2). This opens up new opportunities for space-weather monitoring by using existing radiosonde flights, in the relatively understudied but potentially very important zone between Earth's surface and satellites.

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): the latter detected a decrease in the magnitude of electric field and increase in conductivity (by a factor of two) at 26km (shown in Figure 3). A second balloon at similar altitude but further towards the geomagnetic equator showed no detectable electrical changes, allowing the spatial extent of the SEP event on the electrical environment to be determined. Although the effects of SEPs on atmospheric electrical parameters can be appreciable at high altitudes and at high latitudes, their effects on the GEC are smaller. As suggested by Holzworth and Mozer (1979) and supported by model simulations of the August 1972 SEP event by Reagan *et al*. (1983), the largest changes in GEC parameters (~10% in V_i, J_z and electric field) are related to the change in GCR flux during the Forbush decrease, with little effect of the SEP event on the GEC.

Increased ionisation from SEPs can also potentially lead to changes in the internal global charging current from thunderstorms, which is dependent on stratospheric/mesospheric resistance above a thunderstorm. Model calculations by Farrell and Desch (2002) find that, during large SEP events, the resistance above thunderstorms can decrease sufficiently to increase the upward charging current to the ionosphere. This can affect J_c as well as the surface electric field, however, changes in electric field for even the largest SEP events are only expected to be ~5%.

Ionospheric potential changes

At high latitudes, electrical coupling occurs at high altitudes between the magnetospheric[4] dynamo and the global electric circuit. The ionosphere is considered an equipotential, except over the polar regions, where the solar wind interacts with the geomagnetic field to produce large-scale horizontal electric fields in the ionosphere (sometimes known as the solar wind/magnetosphere dynamo). Horizontal fields of sufficiently large horizontal extent

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[4] The term 'magnetospheric' here refers to the region of space around Earth in which charged particles are controlled by the Earth's magnetic field.

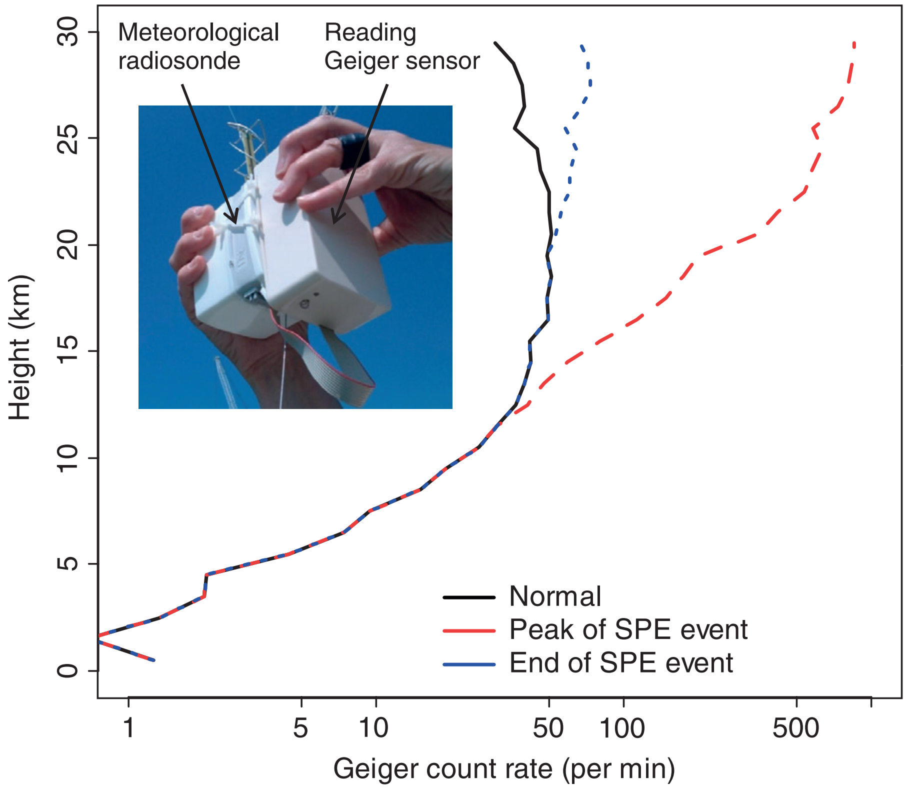

Figure 2. Ionisation measurements from balloon-borne Geiger sensor (showing Geiger count rate) flown from Reading, UK, alongside a standard meteorological radiosonde. The black line denotes the normal ionisation profile due to background galactic cosmic rays, and the red and blue lines are hypothetical profiles at the peak and end of an SEP event respectively. The Geiger count rate is related to the ionisation rate, which in turn relates to the atmospheric electricity parameters of air conductivity and columnar resistance.

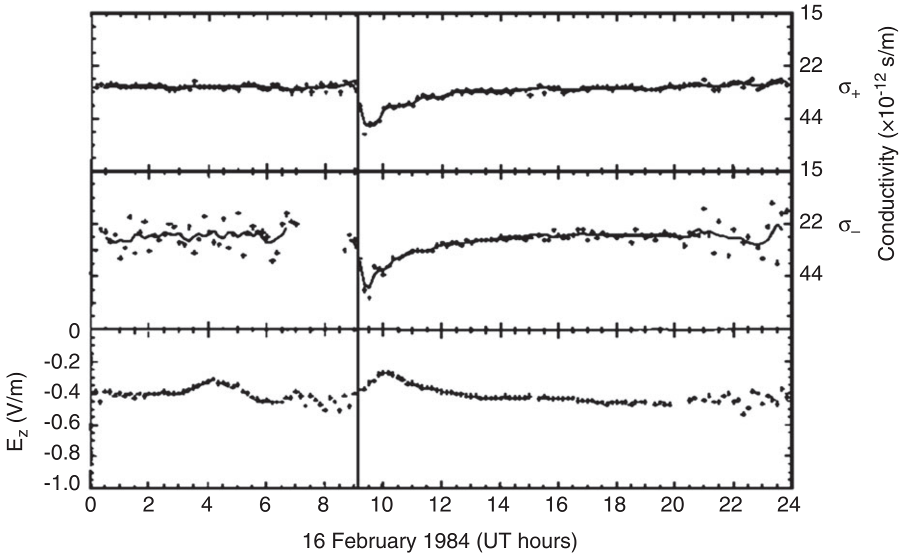

Figure 3. Measurements of atmospheric electrical parameters from a high altitude balloon at 26km during a solar energetic particle event on 16th February 1984 (geographical coordinates 44.6°S, 142.7°E), showing vertical electric field, E_z (left axis) and polar conductivities, σ^+ and σ^- (right axis). The vertical line at 0910 denotes the start of the solar energetic particle event. (Adapted from Holzworth and Norville (1987).)

(500–1000km) can effectively extend down to the surface, creating perturbations in the vertical electric field near the ground (Park, 1976). Such effects are present only at high latitudes, within 30° of the poles, and horizontal V_i variations between dawn and dusk are typically 30–150kV (Roble, 1985). Stratospheric balloon measurements of electric fields show that, during magnetically quiet periods, the classic Carnegie curve is apparent in electric field data, but during more active geomagnetic periods the dawn–dusk potential difference of the magnetospheric convection pattern is seen, superimposed on the Carnegie curve (D'Angelo *et al*., 1982).

Evidence of transfer of magnetospheric disturbances into the troposphere at high latitudes can be seen through the surface electric field measurements of Olson (1971), as well as at mid-latitudes through the work of Kleimenova *et al*. (2008), who demonstrated surface electric-field responses to magnetic substorms[5] from Swider, Poland.

Magnetospheric disturbances can also result in precipitation of relativistic electrons (keV energies), which typically occur at auroral and subauroral latitudes during magnetic substorms and can enhance the conductivity down to the ionospheric D layer[6]. This may lead to redistribution of the downward atmospheric current, generating perturbations in surface measurements of J_c (Belova *et al*., 2000).

Lightning generation

Measurements in thunderstorms indicate that the electric-field strength is an order of magnitude too small to initiate conventional breakdown in air, implying that a more complicated breakdown process occurs. One possible explanation is that GCRs may directly trigger lightning through a mechanism known as 'runaway breakdown', when electrons generated in the particle cascade are accelerated to relativistic energies, developing an electron avalanche that leads to breakdown (e.g. Roussel-Dupré *et al*., 2008). Research by Chronis (2009) demonstrated a decrease in lightning activity 4–5 days after a Forbush decrease in GCR, suggesting that GCRs may play a role in lightning generation, although much more work is required to understand the time-scales involved. Unfortunately work in this field is hampered by high levels of natural variability in thunderstorm occurrence and lightning flash rates, and difficulties with obtaining reliable and consistently calibrated lightning data.

Atmospheric electrical effect on clouds

Although evidence of a space weather influence on atmospheric electrical parameters exists, the solar-electrical coupling mechanisms are not fully understood. Understanding is required in order to assess the consequences of vertical conduction-

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[5] Magnetic substorms occur due to a redistribution of the ionospheric electric field from electric currents in the ionosphere. They are primarily observed over the poles and occur regularly (several times a day, but the exact timings are solar-cycle dependent).

[6] The D layer is the lowest region of the ionosphere (approximately 60–85km).

current flow through clouds (e.g. Tinsley, 2000; Zhou and Tinsley, 2007), which has been observed to charge cloud droplets at the upper and lower boundaries of layer clouds (Nicoll and Harrison, 2010). Electrification of the cloud droplets can have implications for cloud microphysical processes (see e.g. Rycroft *et al*. (2012)), and potentially provides one source of variability in the macroscopic properties of clouds. The sensitivity of the vertical conduction current to variations in solar activity may provide a route by which space-weather changes can couple down through the lower atmosphere to the surface and affect tropospheric processes.

Summary

This paper summarises the various mechanisms by which space weather is thought to affect atmospheric electricity on Earth. These include: ionisation changes from GCRs and SEPs that affect the vertical conductivity profile; interactions between the solar wind and magnetosphere generating horizontal ionospheric electric fields that couple down to the surface; changes in ionospheric conductivity due to precipitating electrons; lightning generation from energetic particles. Although this discussion has separated mechanisms into those that affect conductivity or the ionospheric potential, in reality most space-weather events are a complicated superposition of both of these effects. This means that although evidence of a space weather influence on atmospheric electrical parameters exists (e.g. Harrison *et al*., 2013b), the coupling mechanisms are not well understood. Further work is required to understand the role of changes in the 'disturbed weather', that is, thunderstorms and 'fair weather' part of the circuit, both of which are likely to contribute to changes observed in atmospheric electrical parameters. To further understand the effects of space weather on the GEC, which may in turn also influence clouds, more measurements of atmospheric electrical responses to short-term solar perturbations are required, with high temporal resolution measurements, over a wide range of geomagnetic latitudes. New developments in atmospheric technology allow *in situ* measurement of ionisation rates from GCRs and SEPs simultaneously with atmospheric electrical parameters (Nicoll, 2013) from standard meteorological radiosondes, facilitating new, low cost, space-weather monitoring in the troposphere and stratosphere using the existing operational radiosonde network. Such observations are important to assess the effects of atmospheric electricity on layer clouds, which provides a route by which changes in space weather may couple to lower tropospheric processes.

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