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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, and a downward vertical atmospheric electric field of magnitude $\sim 100\text{V/m}$ observed near the surface during fair weather conditions¹. The origin of the “fair weather field” remained unknown 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 CTR 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 represents the GEC. 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 ($\sim \text{GeV}$ 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 as they interact 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

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

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 . R_c is found by integrating the resistance of atmospheric layers from the surface to the ionosphere, by evaluating

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

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

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 monitor².)

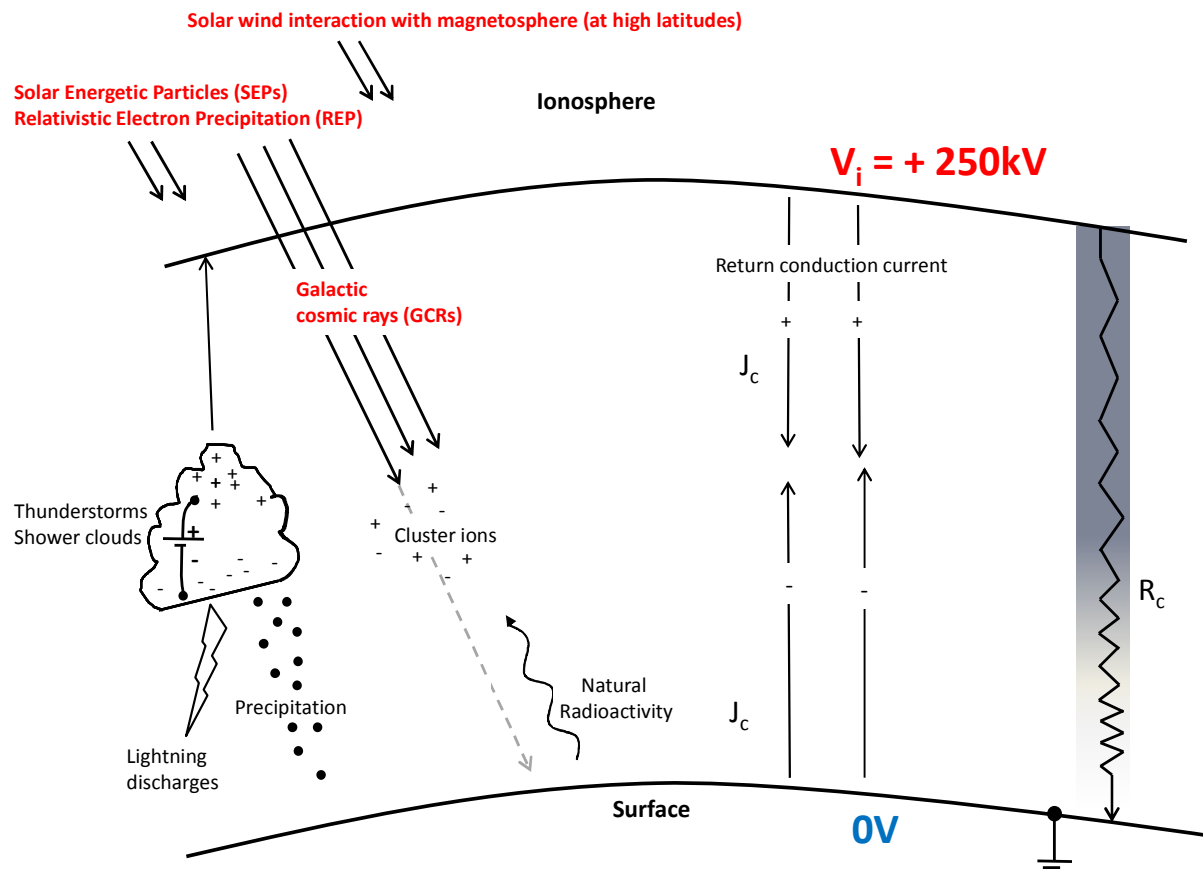


Figure 1. Atmospheric charge generation and transport, including important processes in the global electric circuit. Thunderstorms and electrified shower clouds act as batteries for the circuit, with the current carried by cluster ions, generated by radioactivity and galactic cosmic rays. J_c denotes 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 $+250\text{kV}$ in the ionosphere. Processes known to be related to space weather are depicted in red. Adapted from Rycroft et al (2012).

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 the columnar resistance, 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, geomagnetic³ field variations and ionisation changes

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.

from Solar Energetic Particles (SEPs) and GCRs. 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 section discuss space weather effects on σ and V_i .

(a) Conductivity changes

A variety of space weather related phenomena can modify the ionisation rate and therefore affect the conductivity, 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 like 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 8th August 1972, following solar flares on 2nd, 4th and 7th of 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 ~ 10 V/m), Märcz (1997)), using a superposed epoch analysis technique to combine multiple events.

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 > 500 MeV will generate a cascade of secondary particles through interactions with atmospheric molecules. On rare occasions, when the primary SEPs have energies \approx 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 ~ 50 km, however the associated X-ray Bremsstrahlung produces ionization down to about 20 km (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 SPE 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, 2013), (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 2) at 26km. 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 ($\sim 10\%$ 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 biggest SEP events are only expected to be $\sim 5\%$.

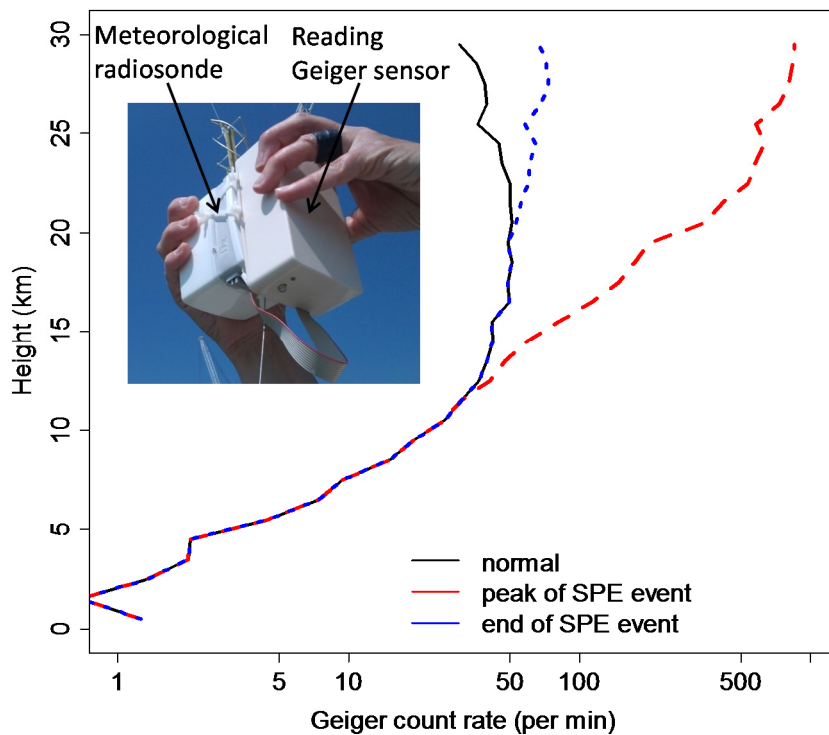


Figure 2. Ionisation measurements from balloon borne Geiger sensor (showing Geiger count rate) flown from Reading, UK, alongside a standard meteorological radiosonde. The black line denotes the normal ionisation profile due to background GCRs and the red and blue lines, hypothetical profiles at the peak and end of an SPE 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.

(b) Ionospheric potential changes

At high latitudes electrical coupling occurs between the magnetospheric⁴ dynamo and the global electric circuit at high altitudes. 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 (500-1000km) can effectively map down to the surface, creating perturbations in vertical electric field near the ground (Park, 1976). Such effects are only present at high latitudes, within 30° of the poles, and horizontal V_i variations between dawn-dusk are typically 30-150kV (Roble, 1985). Stratospheric balloon measurements of electric fields show that, during magnetically quiet periods, the classical Carnegie curve is apparent in electric field data, however 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 substorms⁵ 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 layer⁶. This may lead to redistribution of downward atmospheric current, generating perturbations in surface measurements of J_c (Belova et al., 2000).

(c) 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 which 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 timescales 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.

⁴The term “magnetospheric” here refers to the region of space around Earth in which charged particles are controlled by the Earth’s magnetic field

⁵ Magnetic substorms occur due to a redistribution of 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)

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. This is required to assess the consequences of vertical conduction 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 which affect the vertical conductivity profile; interactions between the solar wind and magnetosphere generating horizontal ionospheric electric fields which couple down to the surface; changes in ionospheric conductivity due to precipitating electrons; and lightning generation from energetic particles. Although this discussion has separated mechanisms into those which 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, the coupling mechanisms are not well understood. Further work is required to understand the role of changes in the “disturbed weather” i.e. 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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