An Overview of Earth's Global Electric Circuit and Atmospheric Conductivity

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Abstract The Earth's global atmospheric electric circuit depends on the upper and lower atmospheric boundaries formed by the ionosphere and the planetary surface. Thunderstorms and electrified rain clouds drive a DC current ($\sim$1 kA) around the circuit, with the current carried by molecular cluster ions; lightning phenomena drive the AC global circuit. The Earth's near-surface conductivity ranges from 10^{-7} S m^{-1} (for poorly conducting rocks) to 10^{-2} S m^{-1} (for clay or wet limestone), with a mean value of 3.2 S m^{-1} for the ocean. Air conductivity inside a thundercloud, and in fair weather regions, depends on location (especially geomagnetic latitude), aerosol pollution and height, and varies from $\sim 10^{-14}$ S m^{-1} just above the surface to 10^{-7} S m^{-1} in the ionosphere at $\sim$80 km altitude. Ionospheric conductivity is a tensor quantity due to the geomagnetic field, and is determined by parameters such as electron density and electron–neutral particle collision frequency. In the current source regions, point discharge (coronal) currents play an important role below electrified clouds; the solar wind-magnetosphere dynamo and the unipolar dynamo due to the terrestrial rotating dipole moment also apply atmospheric potential differences.

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Detailed measurements made near the Earth's surface show that Ohm's law relates the vertical electric field and current density to air conductivity. Stratospheric balloon measurements launched from Antarctica confirm that the downward current density is $\sim$1 pA m^{-2} under fair weather conditions. Fortuitously, a Solar Energetic Particle (SEP) event arrived at Earth during one such balloon flight, changing the observed atmospheric conductivity and electric fields markedly. Recent modelling considers lightning discharge effects on the ionosphere's electric potential ($\sim+250$ kV with respect to the Earth's surface) and hence on the fair weather potential gradient (typically $\sim$130 V m^{-1} close to the Earth's surface. We conclude that cloud-to-ground (CG) lightning discharges make only a small contribution to the ionospheric potential, and that sprites (namely, upward lightning above energetic thunderstorms) only affect the global circuit in a miniscule way. We also investigate the effects of mesoscale convective systems on the global circuit.

Keywords Atmospheric electric circuit · Conductivity models · Fair weather observations · Electrostatic modelling

1 The Global Atmospheric Electric Circuit

The conceptual model of the Earth's global electric circuit has been introduced by Aplin et al. (2008). In brief, the circuit is formed between the Earth's surface, which is a good conductor of electricity, and the ionosphere, a weakly-ionized plasma at $\sim$80 km altitude. Between them is the atmosphere; this is a reasonably good electrical insulator, i.e. it is a leaky dielectric medium. Electrical "batteries" exist below or inside electrified clouds (e.g., thunderclouds); these cause an electric current to flow up to the ionosphere. The "DC" (direct current) electric circuit is completed by downward currents flowing through the majority of the Earth's atmosphere in the "fair weather" region remote from thunderstorms, and through the rocks and oceans of the Earth's crust (Williams 2002; Harrison 2004a; Rycroft 2006; Markson 2007; Rycroft et al. 2007 and references therein).

There is a corresponding "AC" (alternating current) circuit in which phenomena are produced by lightning discharges (Williams 2002). Lightning discharges radiate radio signals across the electromagnetic spectrum, the lowest frequencies of which propagate completely around the globe. These standing wave signals at $\sim$10 Hz excite the resonant cavity formed between the Earth and the ionosphere; these are the so-called Schumann resonances (Schumann 1952). Details of Schumann resonance phenomena are dealt with by Simoes et al. (2008).

2 Conductivities in the Circuit

In general, when considering electromagnetic wave propagation in partially conducting media, with a wave field proportional to $e^{-i\omega t}$, the wave vector k in the medium is defined as ω/v_ϕ. Here v_ϕ is the phase velocity of the wave of angular frequency ω; it is equal to the velocity of light in free space c, divided by the refractive index, η. The refractive index squared, which is equal to the relative permittivity of the medium, ε_r, is given by

$$\eta^2 = \varepsilon_r = 1 + \left(\frac{i\sigma}{\varepsilon_0\omega}\right), \tag{2.1}$$