ATMOSPHERIC ELECTRICITY

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Contents

Summary

An overview of atmospheric electricity area is given, including the global electric circuit, lightning incidence to areas, thundercloud charge structure, and general characterization of lightning, as well as transient luminous events in the middle and upper atmosphere and energetic radiation from thunderstorms and lightning. Every effort has been made to maintain a balance between completeness and an emphasis on the primary features of modern research.

1. Introduction

Systematic studies of atmospheric electricity can be traced back to May 10, 1752 in the village of Marly-la-Ville, near Paris. On that day, in the presence of a nearby storm, a retired French dragoon, acting on instructions from Thomas-Francois Dalibard, drew sparks from a tall iron rod that was insulated from ground by wine bottles. The results of this experiment, proposed by Benjamin Franklin, provided the first direct proof that thunderclouds contain electricity, although several scientists had previously noted the similarity between laboratory sparks and lightning (Prinz, 1977; Tomilin, 1986). The Marly experiment was repeated thereafter in several countries including Italy, Germany, Russia, Holland, England, Sweden, and again France. Franklin himself drew sparks from the probably moist hemp string of a kite after the success at Marly, but before he knew about it (Cohen, 1990). In addition to kites, balloons, mortars, and rockets were used to extend conducting strings into the electric field of the cloud (Prinz, 1977, Figure

5).

In all these experiments, the metallic rod (such as in the experiment at Marly) or the conducting string was polarized by the electric field of the cloud, so that charges of opposite polarities accumulated at the opposite ends of the conductor. As the gap between the bottom end of the conductor and ground was decreased, a spark discharge to ground occurred. The scale and effect of this spark discharge are orders of magnitude smaller than those of lightning. In designing his experiments, Franklin did not consider the possibility of a direct lightning strike to the rod or the kite. Such a strike would almost certainly have killed the experimenter. Thus all those who performed these experiments risked their lives, but there is only one case on record in which a direct strike did occur in such experiments. This happened on August 6, 1753 in St. Petersburg, Russia when Georg Richmann, who had previously done Franklin's experiment, was killed by a direct lightning strike to an ungrounded rod. Interestingly, Richmann was not in contact with the rod, and what caused his death appeared to be a ball lightning that came out of the rod and went to his forehead. Franklin also showed that lightning flashes originate in clouds that are "most commonly in a negative state of electricity, but sometimes in a positive state" (Franklin 1774).

2. The Global Electric Circuit

Shortly after the experiment at Marly that confirmed Franklin's conjecture regarding the electrical nature of thunderstorms, Lemonnier (1752) discovered atmospheric electrical effects in fair weather. Further research established that the Earth's surface is charged negatively and the air is charged positively with the associated vertical electric field in fair weather being about 100 V m^{-1} near the Earth's surface.

2.1. Conductivity of the Atmosphere

The atmosphere below about 50 km is conducting due to the presence of ions created by both cosmic rays and the natural radioactivity of the Earth. Small ions, those with diameters of 0.1 to 1 nm, and life times of about 100 s, are the primary contributors to the conductivity of the lower atmosphere. Free electrons at these heights are attached to neutrals on time scales of the order of microseconds, and their contribution to the conductivity of the atmosphere below about 50 km can be neglected (Gringel et al., 1986; Reid, 1986). Above 60 km or so, free electrons become the major contributors to the atmospheric conductivity. The average production rate of ions at sea level is one to ten million pairs per cubic meter per second. Cosmic rays and natural radioactivity contribute about equally to the production of ions at the land surface. Since large water surfaces have no significant radioactive emanation, the production of ions over oceans is about one half of that over land. At altitudes of roughly 1 km and greater, cosmic rays are responsible for most of the ions in the fair weather atmosphere, regardless of the presence of land below. The ionization rate depends on magnetic latitude and on the solar activity. The electrical conductivity of the air at sea level is about 10^{-14} S m^{-1}, and it increases rapidly with altitude. A diagram illustrating conductivity variations up to an altitude of 120 km is shown in Figure 1. At a height of 35 km, where the air density is about 1% of that at the Earth's surface, the electrical conductivity is greater than 10^{-11} S m^{-1}, which is more than three orders of magnitude higher than at sea level. For comparison, the average electrical conductivity of the Earth is about 10^{-3} S m^{-1}. As seen in Figure 1, a considerable variation of conductivity exists at the same altitude for different measurements, about six orders of magnitude at 60 km. Above about 80 km, the conductivity becomes anisotropic because of the influence of the geomagnetic field, and there are diurnal variations due to solar photoionization processes. Blakeslee et al. (1989) reported, from high-altitude U-2 airplane measurements, that the conductivity near 20 km was relatively steady above storms, with variations being less than ±15%. On the other hand, a number of balloon measurements of the electrical conductivity between 26 and 32 km over thunderstorms suggest that some of the time the storm may significantly (up to a factor of 2) perturb the conductivity (Bering et al., 1980; Holzworth et al., 1986; Pinto et al., 1988; Hu et al., 1989). It is usually assumed that the atmosphere above a height of 60 km or so, under quasi-static conditions, becomes conductive enough to consider it equipotential. The electrical conductivity increases abruptly above about 60 km because of the presence of free electrons (Roble and Tzur, 1986; Reid, 1986). This region of atmosphere just above 60 km or so where free electrons are the major contributors to the conductivity is sometimes referred to as the electrosphere (e.g., Chalmers, 1967) or "equalizing" layer (Dolezalek, 1972). At 100 km altitude (in the lower ionosphere) the conductivity is about 12±2 orders of magnitude (depending on local time) greater than the conductivity near the Earth's surface, that is, the conductivity at 100 km is comparable to the conductivity of the Earth, whether land or sea (Rycroft, 1994).

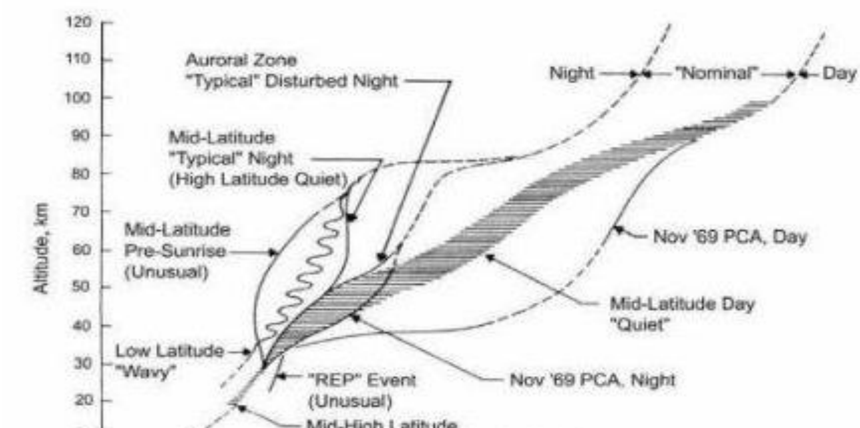

Figure 1. Electrical conductivity σ and corresponding relaxation time $\tau = \varepsilon_0 \sigma^{-1}$, where $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1}, versus altitude under a variety of geophysical conditions. PCA = polar cap absorption event (an unusually large flux of energetic, about 100 MeV solar protons within the polar cap); REP = relativistic electron (few MeV to 10 MeV) precipitation event. Adapted from Hale (1984).

2.2. Fair-weather Electric Field

As noted above, the electric field near the Earth's surface under fair-weather (also called fine-weather) conditions is about 100 V m^{-1}. The electric field vector is directed downward. This downward-directed field is defined as positive according to the "atmospheric electricity" sign convention. According to the alternative sign convention, sometimes referred to as the "physics" sign convention, a downward directed electric field is negative because it is in the direction opposite to that of the radial coordinate vector of the spherical coordinate system whose origin is at the Earth's center. The physics sign convention is used in this chapter. The magnitude of the fair-weather electric field decreases with increasing altitude. For example, according to Volland (1984),

$$E(z) = -[93.8\exp(-4.527z) + 44.4\exp(-0.375z) + 11.8\exp(-0.121z)] \quad (1)$$

where $E(z)$ is the electric field in V m^{-1} (the negative sign indicates that the electric field vector is directed downward) and z is the altitude in kilometers. This equation is valid at midlatitudes below about 60 km altitude and outside thunderstorms or cloudy areas. According to Eq. (1), the electric field at the ground is 150 V m^{-1} and at 10-km altitude decreases to about 3% of its value at the ground. The magnitude of electric field normally drops to around 300 mV m^{-1} at 30 km at midlatitudes (Gringel et al., 1986) and to 1 μV m^{-1} or so at about 85 km (Reid, 1986).

2.3. "Classical" View of Atmospheric Electricity

The evaluation of the line integral of the electric field intensity from the Earth's surface to the height of the electrosphere yields the negative of the potential of the electrosphere, sometimes termed the ionospheric potential (e.g., Markson, 1976), with respect to Earth potential. The potential of the electrosphere is positive with respect to the Earth and its magnitude is about 300 kV, with most of the voltage drop taking place below 20 km where the electric field is relatively large.

The overall situation is often visualized as a lossy spherical capacitor (e.g., Uman, 1974), the outer and inner shells of which are the electrosphere and Earth's surface, respectively. According to this model, the Earth's surface is negatively charged with the total charge magnitude being roughly 5 x 10^5 C, while an equal positive charge is distributed throughout the atmosphere. Little charge resides on the electrosphere "shell." Further, most of the net positive charge is found within 1 km of the Earth's surface, and more than 90% of this charge within 5 km (MacGorman and Rust, 1998). Because the atmosphere between the capacitor "shells" is weakly conducting, there is a fair-weather leakage current of the order of 1 kA (2 pA m^{-2}; 1 pA = 10^{-12} A) between the shells that would neutralize the charge on the Earth and in the atmosphere on a time scale of roughly 10 minutes (depending on the amount of pollution) if there were no charging mechanism to replenish the neutralized charge. Since the capacitor is observed to remain charged, there must be a mechanism or mechanisms acting to resupply that charge. Wilson (1920) suggested that the negative charge on the Earth is maintained by the action of thunderstorms.

Thus all the stormy weather regions worldwide (on average, at any time a total of about 2000 thunderstorms are occurring over about 10% of the Earth's surface) constitute the global thunderstorm generator, while the fair weather regions (about 90% of the globe) can be viewed as a resistive load. Lateral currents are assumed to flow freely along the highly conducting Earth's surface and in the electrosphere. The fair-weather current of the order of 1 kA must be balanced by the total generator current that is composed of currents associated with corona, precipitation, and lightning discharges. The total current flowing from cloud tops to the electrosphere is, on average, about 0.5 A per thunderstorm (Gish and Wait, 1950).

The global electric circuit concept is illustrated in Figure 2. Negative charge is brought to Earth mainly by lightning discharges (most of which transport negative charge to ground) and by corona current under thunderclouds. The net precipitation current is thought to transport positive charge to ground, and its magnitude is comparable to the lightning current (Wahlin, 1986). Positive charge is presumed to leak from cloud tops to the electrosphere. If we divide the potential of the electrosphere, 300 kV, by the fair-weather current, 1 kA, the effective load resistance is 300 ohm.

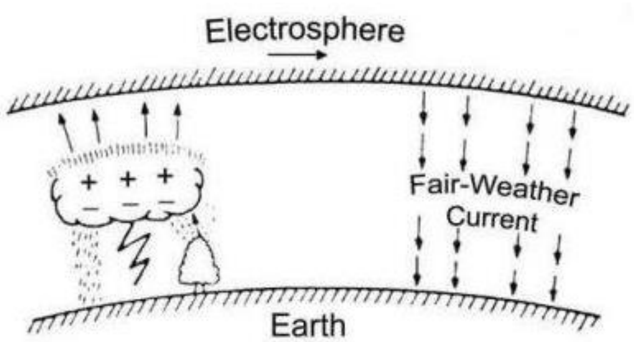

Figure 2. Illustration of the global electric circuit. Schematically shown under the thundercloud are precipitation, lightning, and corona. Adapted from Pierce (1974).

The diurnal variation of the fair-weather field as a function of universal time over the oceans, the so-called Carnegie curve named after the research vessel Carnegie on which the measurements were made (Torreson et al., 1946), appears to follow the diurnal variation of the total worldwide thunderstorm area. Both characteristics exhibit maximum values near 1900 UT and minimum values near 0400 UT. On the other hand, the annual variation of the fair-weather electric field is not in phase with the annual variation of the thunderstorm activity throughout the world (Imyanitov and Chubarina, 1967). Füllekrug et al. (1999) found that the hourly contribution of global cloud-to-ground lightning activity (as represented by magnetic field measurements in the frequency range from 10 to 135 Hz) to the fair-weather electric field in the Antarctic during December 1992 was about 40±10%, and that the contribution to hourly departures from the mean diurnal variation of the electric field was about 25±10%. Holzworth et al. (1984) showed that significant time variations could occur in the global fair-weather current on time scales of 10 minutes to several hours.

According to the classical picture of atmospheric electricity, the layer of the atmosphere extending from about 10 to 200 km and including the stratosphere, mesosphere, and the lower portion of the thermosphere, should be "passive." However, some rocket measurements indicate the existence of strong electric fields (in the volts per meter range, which is orders of magnitude higher than expected in the mesosphere, at altitudes of 50-85 km) of unknown origin (Bragin et al., 1974; Hale and Croskey, 1979; Hale et al., 1981; Maynard et al., 1981; Gonzalez et al., 1982). Interestingly, abnormally strong electric fields are observed near the 60 to 65 km height region, where the "equalizing" layer (electrosphere) is presumed to exist.

Lee and Shepherd (2010) suggested that electrical discharges of some form might be occurring at mesospheric altitudes. The origin of the strong mesospheric fields remains a subject of controversy. Any plausible explanation of this phenomenon must involve either a local mesospheric field generation mechanism or a dramatic local decrease in conductivity.

2.4. Maxwell Current Density

The Maxwell current density $\mathbf{J}_{\mathrm{M}}$ associated with a thunderstorm is defined as the sum of four terms (e.g., Krider and Musser, 1982):

$$\mathbf{J}_{\mathrm{M}} = \mathbf{J}_{\mathrm{E}} + \mathbf{J}_{\mathrm{C}} + \mathbf{J}_{\mathrm{L}} + \varepsilon_0 \left(\frac{\partial \mathbf{E}}{\partial t}\right) \quad (2)$$

where $\mathbf{J}_{\mathrm{E}}$ is the field dependent current density which may include both linear (ohmic: $\mathbf{J} = \sigma \mathbf{E}$ where σ is the electrical conductivity) and nonlinear (corona) components, $\mathbf{J}_{\mathrm{C}}$ is the convection current density which may include a contribution from precipitation, $\mathbf{J}_{\mathrm{L}}$ is the lightning current density, and the last term is the displacement current density.

In planar geometry, this current density is the same at any height in the atmosphere, as required by the current continuity equation (e.g., Sadiku, 1994). Krider and Musser (1982) suggested that the thundercloud, the postulated source in the global electric circuit, can be viewed as a current source which produces a quasi-static Maxwell current density even in the presence of lightning. In this view, the thunderstorm generator in the global electric circuit can, in principle, be monitored through its Maxwell current density.

The total Maxwell current density under thunderstorms has been measured by Krider and Blakeslee (1985), Deaver and Krider (1991), and Blakeslee and Krider (1992). Krider and Blakeslee (1985) found that the amplitude of $\mathbf{J}_{\mathrm{M}}$ is of the order of 10 nA m^{-2} under active storms, while Deaver and Krider (1991) reported amplitudes of the order of 1 nA m^{-2} or less (in the absence of precipitations) under small Florida storms.

Above the thunderstorms, the convection and lightning terms, $\mathbf{J}_{\mathrm{C}}$ and $\mathbf{J}_{\mathrm{L}}$, in Eq. (2) are assumed to be negligible, and the Maxwell current density is expressed as the sum of only two terms:

$$\mathbf{J}_{\mathrm{M}} = \mathbf{J}_{\mathrm{E}} + \varepsilon_0 \left(\frac{\partial \mathbf{E}}{\partial t}\right) \qquad (3)$$

The Maxwell current density at altitudes of 16-20 km has been measured by Blakeslee et al. (1989). They found that $\mathbf{J}_{\mathrm{E}}$ typically accounted for more than half of $\mathbf{J}_{\mathrm{M}}$, while at the ground $\mathbf{J}_{\mathrm{M}}$ is generally dominated by the displacement current density during active storm periods as long as the fields are below the corona threshold of a few kV m^{-1} and there is no precipitation current.

It is thought that, under some conditions, the Maxwell current density may be coupled directly to the meteorological structure of the storm and/or the storm dynamics (Krider and Roble, 1986, pp. 5-6). However, the lack of simultaneous Maxwell current measurements both on the ground and aloft has not allowed the details of this relationship to be determined.

2.5. Modeling of the Global Circuit

Models that can be used to calculate the electric field or the potential distribution around the thundercloud and the current that flows from a thundercloud into the global electric circuit have been developed by Holzer and Saxon (1952), Kasemir (1959), Illingworth (1972a), Dejnakarintra and Park (1974), Hays and Roble (1979), Tzur and Roble (1985b), Nisbet (1983, 1985a,b), Browning et al. (1987), Hager et al. (1989a,b), Driscoll et al. (1992), Stansbery et al. (1993), Hager (1998), and Plotkin (1999). Both analytical and numerical models have been developed. Some models (e.g., Holzer and Saxon, 1952; Hays and Roble, 1979; Tzur and Roble, 1985b) are based on a quasi-static approximation, while other models (e.g., Illingworth, 1972a; Dejnakarintra and Park, 1974; Driscoll et al., 1992) are designed to deal with a time varying problem including the effects of lightning. Nisbet (1983) modeled the atmosphere with a network of resistors, capacitors, and switches, where the current through these circuit elements represented conduction, displacement, and lightning currents, respectively. Sometimes corona currents are taken into account (e.g., Tzur and Roble, 1985b). Convection currents (including those due to precipitation) are usually neglected. These models provide a convenient means of examining, through numerical experiments, the various processes operating in the global circuit. Heights up to 100-150 km are usually considered. Thunderclouds are usually represented by two vertically displaced point charges of opposite polarity maintained by a current source. The upward-directed current from thunderclouds is assumed to spread out in the ionosphere of the storm hemisphere and, in some models (e.g., Hays and Roble, 1979; Tzur and Roble, 1985b; Browning et al., 1987; Stansbery et al., 1993) to flow along the Earth's magnetic field lines into the conjugate hemisphere. According to Stansbery et al. (1993), approximately half of the current that reaches the ionosphere flows into the conjugate hemisphere, and the other half of this current flows to Earth in the fair-weather regions of the storm hemisphere.

Anisimov and Mareev (2008) consider the global electric circuit as an open dissipative system including microphysical and electrohydrodynamic processes of generation and dissipation of the aeroelectric energy. They also stress the importance of studying nonstationary processes and, in particular, short-period (10^{-3}–1 Hz) electric pulsations of fair weather fields.

2.6. Alternative Views of the Global Circuit

Wilson's suggestion that thunderstorms are the main driving element in the atmospheric global circuit has been questioned by, among others, Dolezalek (1972), Williams and Heckman (1993), Kasemir (1994), and Kundt and Thuma (1999). Dolezalek (1988) suggested that the net charge on the Earth may be zero or near zero, rather than the 5 x 10^5 C postulated in the classical model of atmospheric electricity. Kasemir (1994) proposed an alternative concept of the global circuit in which the only equipotential layer is the Earth. He assumes that the very high negative potential of the Earth with respect to infinity drives the fair-weather current. Lightning discharges and corona at the ground are claimed to be "local affairs" that do not contribute to the global circuit. In Kasemir's view, there are two types of generators in the global circuit, convection (acting in both stormy and fair-weather regions) and precipitation, both generators being driven by non-electrical forces. Kundt and Thuma (1999), based on their estimate of relatively low cloud top voltage of 1 MV (relative to the Earth), asserted that thunderstorms are not important in the global electric circuit. However, Marshall and Stolzenburg (2001), from 13 balloon soundings of electric field through both convective regions and stratiform clouds, reported cloud top voltages ranging from -23 to +79 MV, with an average of +25 MV. The average cloud top voltage for the nine cases with positive values was +41 MV. Marshall and Stolzenburg (2001) consider these voltage values as supporting Wilson's hypothesis that thunderstorms drive the global electric circuit. Further, Marshall and Stolzenburg (2001) estimated the average cloud top voltage of +32 MV for electrified stratiform clouds, this finding suggesting that stratiform clouds may make a substantial contribution to the global electric circuit.

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Biographical Sketch

Vladimir A. Rakov received the M.S. and Ph.D. degrees in electrical engineering from the Tomsk Polytechnical University (Tomsk Polytechnic), Russia, in 1977 and 1983, respectively. From 1977 to 1979, he worked as an Assistant Professor of electrical engineering at Tomsk Polytechnic. In 1978, he became involved in lightning research at the High Voltage Research Institute (a division of Tomsk Polytechnic), where from 1984 to 1994, he held the position of the Director of the Lightning Research

Laboratory. He is currently a Professor at the Department of Electrical and Computer Engineering, University of Florida, Gainesville, and Co-Director of the International Center for Lightning Research and Testing (ICLRT). He is the author or coauthor of 2 books, 19 book chapters, 32 patents, and over 600 other publications on various aspects of lightning, with over 220 papers being published in reviewed journals. Dr. Rakov is Editor or Associate Editor of three technical journals, Co-Chairman of URSI WG E.4 "Lightning Discharges and Related Phenomena", and Convener of CIGRE WG C4.407 "Lightning Parameters for Engineering Applications". He is a Fellow of four major professional societies, the IEEE, the American Meteorological Union, the American Geophysical Society, and the Institution of Engineering and Technology (formerly IEE).