Fair weather atmospheric electricity: its origin and applications

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***Abstract*—An entirely electrostatic view of the earth - upper atmosphere system, as understood for example, by Lord Kelvin, underwent a paradigm shift around 1900 with definitive observations of sustained ion production in atmospheric air. Cosmic ray ionisation of atmospheric air, together with a potential difference between the upper atmosphere and the earth's surface, yield vertical atmospheric current flow in regions of fair weather. The current's origin was ultimately explained through the global circuit model of the Scottish atmospheric physicist C.T.R. Wilson, Nobel prize recipient for the cloud chamber. In Wilson's conceptual model, charge exchanged by disturbed weather electrifies the ionosphere, with a return current flowing in fair weather regions. Sources of internal (thunderstorms) and external (energetic particles and cosmic rays) earth system variability can therefore influence the global circuit and the current flowing. One situation, of particular interest because it occurs commonly globally, is when the vertical current passes through an extensive horizontal cloud layer. As the electrical conductivity is reduced in cloudy air compared with clear air, charge accumulates at the upper and lower boundaries of the layer clouds in the vertical current flow if the cloud-air conductivity transition is sharp. Changes in the current flow which arise from a variety of sources (e.g. climate system variability, space weather or even the radon gas release associated with some earthquakes) can therefore potentially be communicated into clouds. New insights into the global relevance of fair weather atmospheric electricity are now emerging through novel instrumentation and measurements, arising from the close relationships between energetic particles, ions, aerosol and cloud droplets.**

I. Introduction

Atmospheric Electricity is one of the longest-standing active research areas in the geosciences. Its quantitative beginnings are usually traced to the eighteenth century, primarily because of the almost universally known work of Benjamin Franklin [1], and the inadvertent thunderstorm experiment of Thomas François-Dalibard at Marly-la-Ville, France on 10th May 1752 it inspired [2]. Soon afterwards it was observed that the atmosphere remains electrified even in the absence of thunderstorm activity [3,4], indirectly establishing the study of *fair weather* atmospheric electricity which continues today.

Many of the early fundamental atmospheric investigations used basic mechanical electrometers, which, as well as providing information on the variability which is characteristic of the electric fields present in the atmosphere, indicated the complexity concerned with the electrification of droplets in fogs [5] and, by implication, that of clouds. In the early nineteenth century electrostatic displays and demonstrations were highly fashionable, so offered a convenient explanatory framework for intriguing natural phenomena, such as the differing appearances of clouds [6]. Indeed in the pioneering manned balloon ascents of the 1860s an electrometer was regarded as an essential piece of instrumentation. Through these measurement technologies, intermittent data series are available for modern analysis, notably, in London, from Knightsbridge [7] and Kew Observatory [8],

No doubt because of the complexity and variability encountered whilst making atmospheric measurements, the great classical physicist Lord Kelvin recognized the need for instruments able to maintain a continuous record of their measurements. In an intense phase of work in 1859 [9] – by any standard an *annus mirabilis* – Kelvin made great advances with sensor and recording technologies, the latter exploiting photographic techniques. Closely related methodologies were implemented across the UK internationally [10], such as at the top of the Eiffel Tower [11], and even remain in use at Kakioka Observatory, Japan.

II. Global Circuit Concept

The modern era of fair weather atmospheric electricity follows the discovery, made almost simultaneously in the UK and Germany at the end of the nineteenth century, that air is continuously ionized [12]. This finding challenged the then existing conceptual ideas – championed, amongst others, by Kelvin - that the Earth's charge resided in the upper atmosphere and was essentially constant. This perspective became untenable due to dissipation of the charge that is associated with the ionization. Consequently atmospheric electricity developed from the study of electrostatic phenomena to understanding the origin of charge generation and rates of charge exchange through the atmosphere.

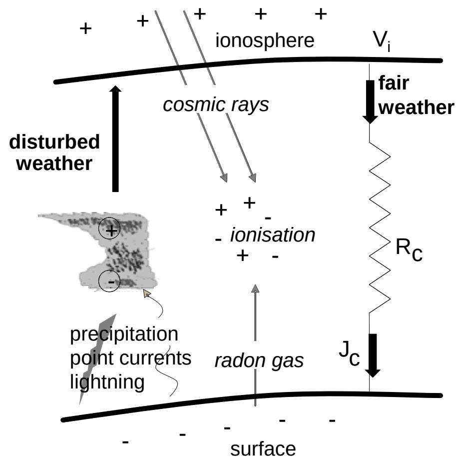

Fig 1. The global atmospheric electric circuit. Charge separation in disturbed weather regions drives current through the ionosphere, fair weather zones and the surface. The quantities of the ionospheric potential V_i, (~ +250 kV), conduction current density J_c (~2 pA m^{-2}) and unit area columnar resistance R_c are, assuming a one-dimensional system, related by Ohm's Law.

The Scottish physicist C.T.R.Wilson who had discovered the ionization (and was later winner of the 1927 Nobel prize for inventing, inspired by meteorological observations, the cloud chamber [13] to visualize the behavior of cosmic rays) went on to establish the existence of vertical current flow in the fair weather atmosphere [14]. From well-calibrated measurements of great ingenuity, the current flowing globally in the atmosphere could be estimated. Wilson used this to deduce that charge separation in thunderstorms and disturbed weather regions balanced the fair weather current flow, via the good conductivity (relative to air), of the planetary surface and ionized upper atmosphere (figure 1).

A variety of subsequent observations have confirmed the global atmospheric electric circuit as a broadly correct conceptual model [15], although the current flow in polar regions differs and the details of the charge exchange above and below disturbed weather regions are still being resolved. Strong initial support for the global circuit concept came from investigations of the diurnal cycle observed in atmospheric electric properties, such as the vertical electric field E_z near the surface, also known as the Potential Gradient F (where F=-E_z, and in clean air at the surface, F ~ 120 Vm^{-1}.) From extensive studies made by an ocean survey ship, the *Carnegie*, it was found that the same diurnal variation in F (referenced to Universal Time, UT) occurred (fig 2a), wherever it was measured globally in oceanic air during fair weather [16]. The phasing of the daily variation – the Carnegie curve – was shown to be related to the variation in active thunderstorms, which varies across the day with the local solar heating (fig 2b). If the total global area of active thunderstorms is calculated, its variation over the day is found to be closely correlated with the Carnegie curve (fig 2c).

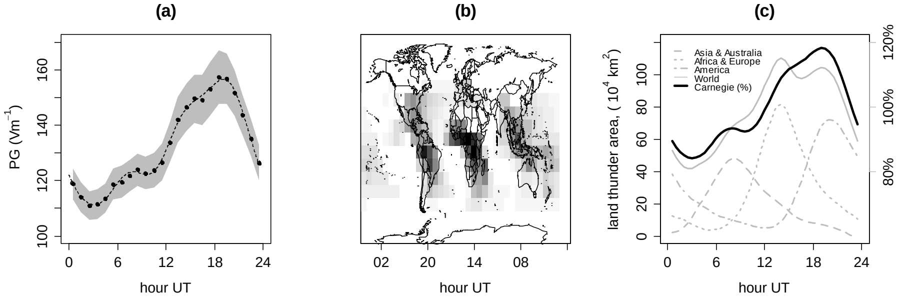

Fig 2. (a) Diurnal variation in surface Potential Gradient (PG) averaged from measurements made on cruise VII of the *Carnegie* during 1928 and 1929 (grey shading shows 95% confidence range on the mean values). (b) Geographical distribution of the annual totals of days on which thunder was heard [17]. (c) Comparison of the diurnal variation in thunderstorm area summed globally, and the Carnegie curve [18].

III. LAYER CLOUDS AND CURRENT FLOW

The conduction current of the global circuit J_c is always present globally in fair weather, and is sensitive to both internal climate variations affecting thunderstorms (such as the El Niño Pacific ocean sea surface warmings), and external sources of ionisation such as solar energetic particles and cosmic rays. Clouds are atmospheric regions where the air has a reduced electrical conductivity compared with clear air, hence, should this vertical current encounter an extensive region of cloud, electrification at the upper and lower edges of the cloud layer must result at the conductivity transition. The space charge density ρ is proportional to the vertical gradient in conductivity and the current flowing, given, in one dimension, by

$$\rho = \varepsilon_0 J_c \frac{1}{\sigma^2}\frac{d\sigma}{dz} \tag{1}$$

where σ is the air conductivity, z is the vertical coordinate and ε_0 is the permittivity of free space. The cloud edge charging therefore depends on the meteorological conditions determining the properties of the cloud edge and the global circuit-dependent parameter J_c.

Fig 3 shows examples of the use of equation (1), after making some assumptions about the properties of a thin cloud layer consisting of uniformly distributed droplets of the same size. Fig 3a and 3b demonstrate these assumptions, specifically that (a) the number of droplets increases at the base of the cloud layer, is constant within the layer, and decreases sharply at the cloud top. (b) shows the assumptions made concerning the growth in size of droplets; at cloud base, the droplets are freshly formed on cloud condensation nuclei, and then grow in the weak updrafts associated with the cloud until they evaporate at the cloud top. (c) summarises the consequences of these assumptions in terms of the visual range which results: the visual range is appreciable beneath and above the cloud, and of course much diminished within the cloud. The assumptions concerning the droplet concentrations and size variations at the cloud base and cloud top also define the visual variations at the upper and lower boundaries.

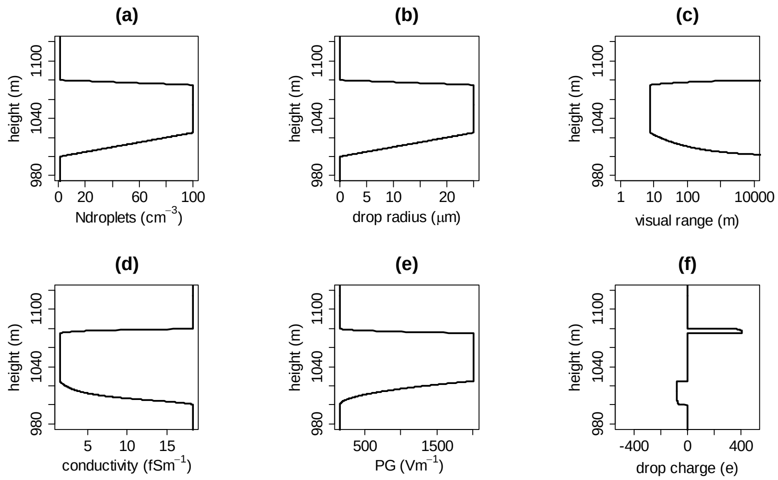

Fig 3. Variations in electrical properties, for an idealized cloud layer of droplets. (a) and (b) show the assumed cloud droplet concentration and size, with (c) the derived visual range from these properties. (d) and (e) show the air conductivity and vertical potential gradient, assuming J_c=3pAm^{-2}. (f) shows the associated variation in mean charge per droplet.

Fig 3d shows the calculated air conductivity outside and within the cloud. This calculation uses the ion balance equation [19] to determine the steady-state ion concentration, assuming the ion production rate q (4 cm^{-3} s^{-1}) and ion mobility μ (1.2 V^{-1}m^{-1}s^{-2}). From the air conductivity variation, and assuming a constant J_c, the vertical Potential Gradient PG can be found from Ohm's Law (fig 3e). Finally, from equation (1), the droplet concentration profile (fig 3a) and the conductivity profile (fig 3d), the mean charge per droplet can be calculated. Clearly the mean charge per droplet is closely related to the conductivity gradients at the cloud base and cloud top, which, in turn, depend on the vertical profiles of the droplet properties. A close relationship is therefore also expected between quantities depending on the droplet properties, notably the optical (visual range) and electrical (droplet charge) parameters [20].

Measurements of the cloud edge electrification in real atmospheric conditions require a suitable platform to allow the clouds to be reached, charge detectors, and reliable information on the cloud boundary structure. Investigations have recently been made using a modified weather balloon system [21], to allow standard meteorological measurements of temperature, pressure, relative humidity and GPS location to be combined with the electrical measurements. A sample sounding using this equipment is shown in fig 4.

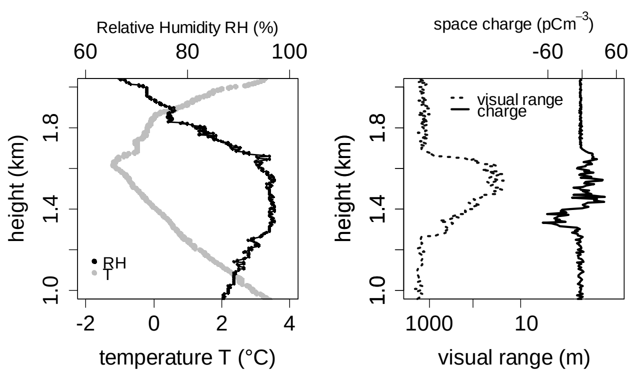

Fig 4. Vertical sounding through a layer cloud showing meteorological properties of temperature T and relative humidity RH (left), and droplet-derived properties (right) of visual range and droplet charge.

In the left hand panel the variation of temperature and relative humidity determined by the rising balloon can be seen. The relative humidity increases in the cloud layer and the decrease of temperature ceases at the cloud top, where it begins to slightly increase. However, as is clear from fig 4, the standard meteorological measurements of temperature and relative humidity are insufficient to determine the cloud edge parameters accurately; an improved approach has instead been developed specially, based on an optical method employing a high brightness LED [22]. A charge sensor has also been developed, based on the displacement current principle for a moving electrode [23]. Fig 4 shows that the charge observed in an atmospheric cloud layer using these technologies responds to the cloud boundary properties as expected from theory.

For small droplets, such as those on the cloud edge where the charging occurs, charge is expected to influence the collision properties and evaporation [24]. Because the droplets are polarizable, at short ranges, image forces become important and the interactions between an infinite set of image charges must be summed: this leads to the droplet-droplet force always being attractive at short range, independent of the relative polarity of the droplets (Fig 5).

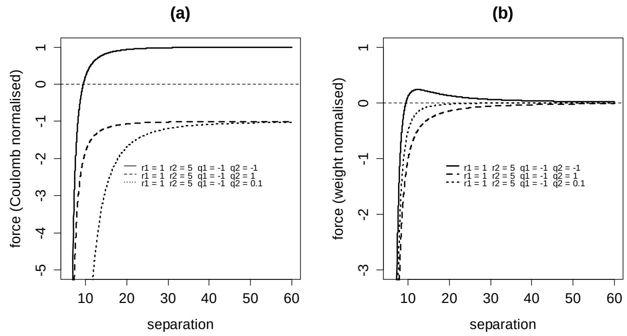

Fig 5. Calculation of the variation in the total electrical force with separation, between droplets of radii r_1 and r_2, carrying charges q_1 and q_2. The forces have been normalized to (left panel) the long range Coulomb force between point charges and (right panel) the weight of the smaller droplet. In both cases, negative forces represent attraction.

IV. Other Applications

Fair weather atmospheric electric fields show sensitive variations in response to changes in the atmospheric environment. Because long records of the Potential Gradient exist at some sites, information is in principle available about historical atmospheric properties. This can be used to reconstruct past air pollution conditions, which are relevant to understanding past climate changes associated with black carbon loadings [25], or study seismic changes which linked to release of radon gas [26]. Changes in the space weather environment associated with transient or sustained ionisation also appear to be closely coupled to the lower atmosphere through atmospheric electricity, and therefore, potentially, following the arguments above, into cloud properties [27].

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