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## Fair weather atmospheric electricity

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**Abstract.** Not long after Franklin's iconic studies, an atmospheric electric field was discovered in "fair weather" regions, well away from thunderstorms. The origin of the fair weather field was sought by Lord Kelvin, through development of electrostatic instrumentation and early data logging techniques, but was ultimately explained through the global circuit model of C.T.R. Wilson. In Wilson's model, charge exchanged by disturbed weather electrifies the ionosphere, and returns via a small vertical current density in fair weather regions. New insights into the relevance of fair weather atmospheric electricity to terrestrial and planetary atmospheres are now emerging. For example, there is a possible role of the global circuit current density in atmospheric processes, such as cloud formation. Beyond natural atmospheric processes, a novel practical application is the use of early atmospheric electrostatic investigations to provide quantitative information on past urban air pollution.

*The material summarised here was presented in the Bill Bright memorial lecture at Electrostatics 2011.*

### 1. Historical perspective

Benjamin Franklin's findings opened a new era in electrostatics, of central importance in establishing the science of atmospheric electricity. Discovering [1] the similarity between electricity in thunderclouds and that generated by machines by kite and rod experiments began the study of thunderstorm electricity, but, with it, an awareness also emerged that electrification remained apparent despite the absence of thunderstorms, even, to use an early description, in "serene" (*i.e.* fine) weather conditions.

Early direct observations of terrestrial fair weather electrification were made in summer 1753, no doubt inspired by Franklin's work. For example, at the Château de Maintenon, Abbé Mazeas established a long wire antenna system for electrical atmospheric measurements [2],

*"On the 14<sup>th</sup> of June I accompanied the Marcehal de Noailles to his castle of Maintenon. At my arrival, I set up an apparatus, which consisted of an iron wire 370 feet long, raised to 90 feet above the horizon. It came down from a very high room in the castle, where it was fastened to a silken cord six feet long, and was carried from thence to the steeple of the town; where it was likewise fastened to another silken cord of eight feet long, and shelter'd from rain..."*

finding that

*“...in weather void of storms, the electricity of a piece of sealing-wax of two inches long was about twice as strong as that of the air.”*

Experiments on thundercloud electrification using a rain-shielded electrometer were undertaken in the UK from May 1753 by John Canton [3], which led him to conclude [4], specifically for fine conditions rather than just storm-free conditions, that

*“The air without-doors I have sometimes known to be electrical in clear weather.”*

Several other series of atmospheric electricity experiments are known to have been made through the late eighteenth and nineteenth centuries, notably the heroic continuous observations of Giambatista Beccaria in Piedmont, north-west Italy [5], which inspired Lord Kelvin to develop an “incessant” automatic photographic recording system for his water dropper electrometer [6]. Kelvin’s well calibrated instrumentation allowed quantitative observations of the atmospheric electric field’s vertical component,  $E_z$ , to be obtained, conventionally recorded as the Potential Gradient  $F$ , where  $F = -E_z$ . Converted to modern units [7], Kelvin’s determination of the fair weather PG near Aberdeen, Scotland at 0800 on 14<sup>th</sup> September, 1859 was  $+137 \text{ Vm}^{-1}$ .

## 2. Synthesis of observations in the global atmospheric electric circuit

Although the first century of atmospheric electricity observations confirmed the continuous presence of an electric field in fair weather conditions, its origin remained a key geophysical problem. Further discoveries around the beginning of the twentieth century, such as the vertical profile of the ionization generated by cosmic rays, and confirmation, by radio, of a conducting region in the upper atmosphere allowed C.T.R. Wilson to propose the existence of an atmospheric electrical circuit. This synthesis drew heavily on the established electrostatic and geophysical observations made since 1753, together representing “central tenets” of the global circuit [8], Table 1.

<i>Century</i>	<i>Observation</i>	<i>Investigators</i>
18 <sup>th</sup>	Finite conductivity of atmospheric air	Coulomb
19 <sup>th</sup>	Fair weather positive Potential Gradient	Kelvin
	Continual atmospheric ionisation	Wilson
20 <sup>th</sup>	Upper atmosphere highly conductive	Heaviside, Kennelly, Marconi
	Vertical current flow in fair weather	Wilson
	Cosmic ray atmospheric ionization profile	Hess
	Finite conductivity of earth’s surface	Chapman

Table 1. “Central tenets” of the global atmospheric electrical circuit.

Wilson’s conceptual model linked current generation in disturbed weather zones (thunderstorms and shower clouds acting as “generators”) with the fair weather zones, by an electrical connection through the conductivity of the upper atmosphere and the surface (Figure 1a).

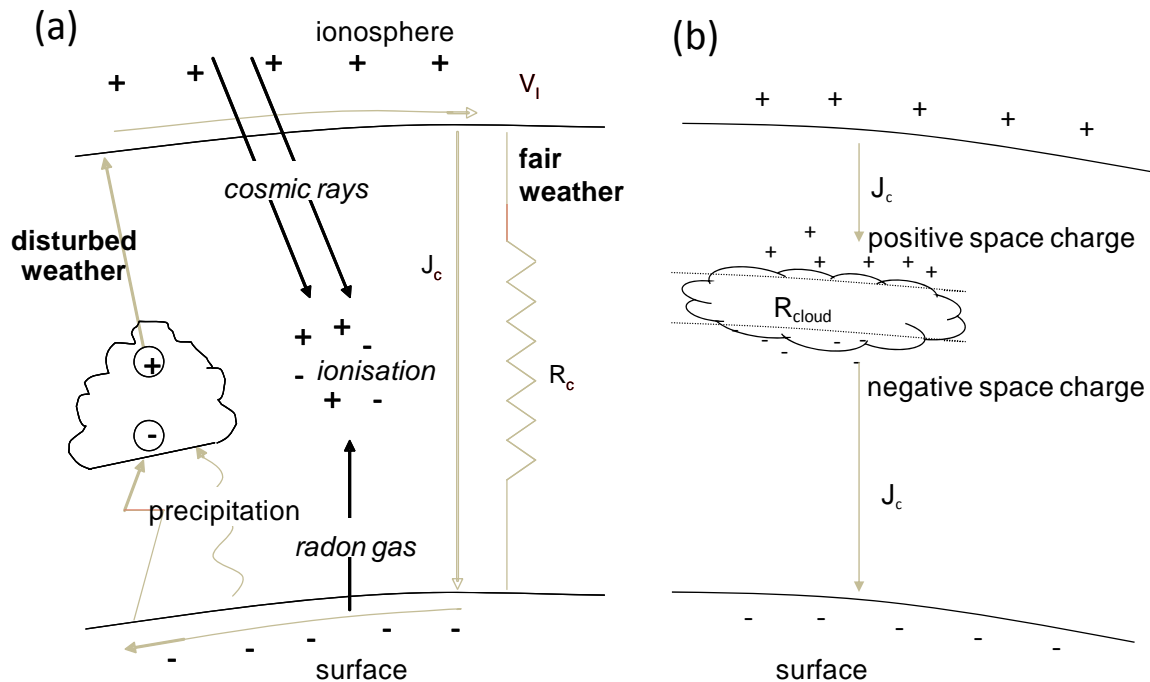


Figure 1. (a) The global atmospheric electric circuit. Charge generated in disturbed weather zones drives current through the ionosphere and back through the surface, with intermediate current flow through the finite air conductivity in fair weather zones. The ionospheric potential  $V_i$  ( $\sim +250$  kV), conduction current density  $J_c$  ( $\sim 2$  pA  $m^{-2}$ ) and unit area columnar resistance  $R_c$  are approximately related by Ohm's Law. (b) Vertical current flow in the fair weather zone of the global circuit, through an extensive horizontal resistive cloud layer.

### 3. Fair weather measurements

Subsequent studies have acted to confirm the global circuit concept [8], such as agreement between the diurnal variations in the global thunderstorm generator, the PG in clean air, and the ionospheric potential. Many additional measurements are now available, but the fair weather region of the global circuit has probably received less attention than the disturbed weather region. In part this may be due to the difficulty in correcting local site-dependent factors, and the technical challenge in maintaining high integrity insulation for reliable measurements of small currents. PG measurements are the most common, made straightforward by environmentally robust field mill technology [6, 9]. Table 2 summarises PG measurements made at Reading under different weather conditions. The field mill was standardised to a measurement at 1m by calibration against a long wire antenna.

The raw data from which Table 2 was derived are presented as histograms in Figure 2, with the classification of the different weather conditions used briefly described. (Solar radiation measurements were used to infer cloud.) These histograms clearly indicate that the PG varies with weather conditions, showing distributions skewed negative in rain, and strongly positive in fog. Fair weather PG values, as long recognized, are positive, as are the PG values determined during non-raining overcast conditions. It is evident from Table 2 that the PG in overcast conditions is slightly reduced over that obtained in clear conditions. This would be associated with an increase in the columnar resistance, as a result of the increased resistance of the cloud layer over clear air, although the relative contribution to the columnar resistance will vary with the depth and height of the cloud layer present.

Weather conditions	Median PG ( $\text{Vm}^{-1}$ )	PG variability (IQR/1.349) ( $\text{Vm}^{-1}$ )	hours of data
all conditions	80.6	42.9	8447
snow	191.6	36.1	22
fog	170.6	105.3	139
clear sky	93.5	32.2	177
broken cloud on dry days	91.1	30.9	349
overcast on dry days	81.4	33.1	479
heavy rain	-4.9	133.4	174

Table 2. Summary of Reading Observatory PG measurements in 2010. (The variability is expressed in terms of the Inter-Quartile Range IQR, scaled to be equal to one standard deviation if the distribution were normal.)

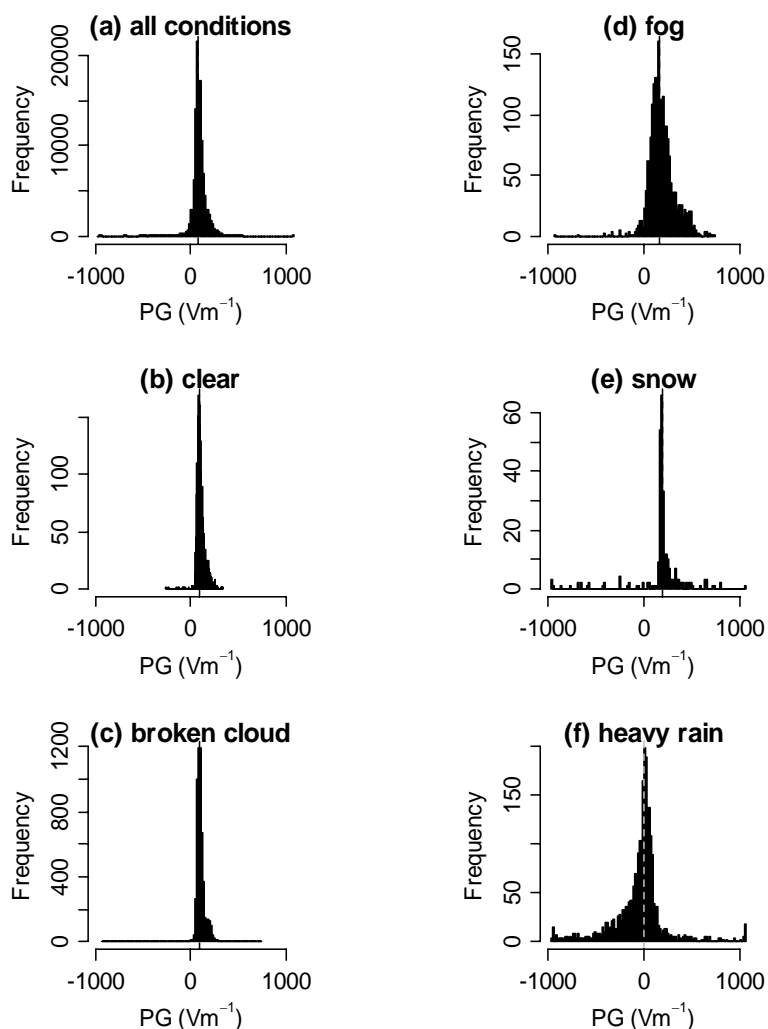


Figure 2. Histograms of Potential Gradient (PG) (5 minute averages) made at Reading Observatory during 2010, for (a) all weather conditions, (b) clear days, (c) broken cloud on dry days, (d) fog (wet bulb and dry bulb temperatures equal, with relative humidity > 90%), (e) snow (recorded by observer) and (f) heavy rain (> 4mm/hour).

A succinct visual summary of the PG data in Table 2 can be made by plotting the variability against the median for the different weather types, as shown in figure 3. This representation shows the distinction in electrical conditions between rain, fog and snow, which can be difficult to separate using some automated monitoring systems. Atmospheric electricity data may therefore aid classification of weather conditions for automatic weather stations.

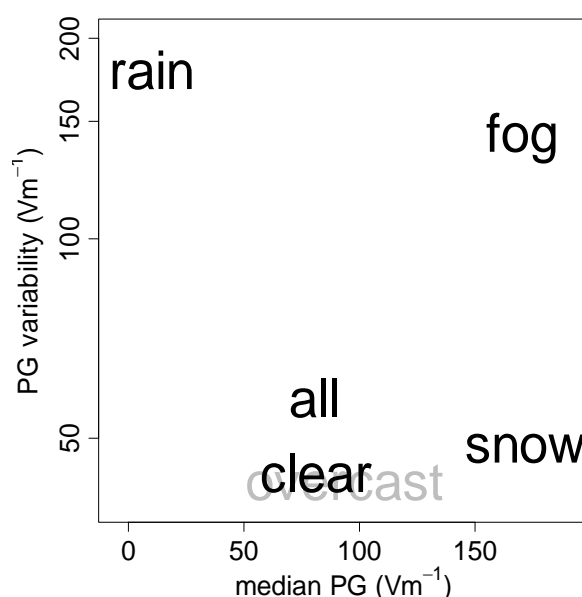


Figure 3. Representation of the PG data obtained during a variety of weather conditions at Reading during 2010, as summarized in Table 2.

Observations of the sensitivity of atmospheric electrical properties to weather changes seems very likely to have formed the basis for the famous comment [10] of Lord Kelvin concerning weather forecasting:

*“There can be no doubt but the electric indications, when sufficiently studied, will be found important additions to our means for prognosticating the weather; and the speaker hoped soon to see the atmospheric electrometer generally adopted as a useful and convenient weather-glass.”*

#### 4. Applications and outstanding problems

Because of its linkage between different regions of the planet, the global circuit potentially provides a monitoring framework able to provide corroborating information relevant to climate change. Changes in thunderstorm activity for example, may lead to a change in the ionospheric potential and associated global circuit variables, but the details of such changes are complex and poorly known [11]. On the more local scale, an application for the many urban measurements of the PG is in reconstructing past air pollution burdens. This is because the PG is sensitive to smoke pollution [12], which provides quantitative relationship allowing smoke concentrations in some past urban situations to be inferred from atmospheric potential measurements. For example, using eighteenth century electrostatic measurements, it has been possible to establish that a two maxima per day existed in London’s smoke pollution before the advent of motor traffic [13].

Beyond the traditional fair weather regime of an electrically quiescent atmosphere, the intermediate “semi-fair weather conditions” raises many new science questions. Firstly, charge generated in lofted

atmospheric particles, such as the ash produced by the April 2010 eruption of Eyjafjallajökull [14] provides an opportunity to use low cost detection technologies. Secondly, the sensitivity of the global circuit to surface ionization may allow observation of widespread geological changes in radon emission, which could be a precursor phenomenon for some earthquakes [15]. Finally, when the vertical conduction current density of the global circuit encounters horizontal layers of dust or clouds, the abrupt reduction of air conductivity in the transition from clear air to cloudy air leads to space charge on the cloud boundary (this process is illustrated in Figure 1(b)). This may in turn influence the properties of the clouds and, perhaps, climate. In some respects this leads back to the historical aspects discussed in section 1, and particularly to the fashions of early electrostatics in speculating on cloud phenomena. This era is epitomized in the writings of the pioneer meteorologist Luke Howard, who described the shower cloud *Nimbus* as one

“in which minute drops constituting cloud...are by a change in their electrical state made to coalesce, and descend in drops of Rain”. [16]

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