Observed atmospheric electricity effect on clouds

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Abstract
The atmosphere’s fair weather electric field is a permanent feature, arising from the combination of distant thunderstorms, Earth’s conducting surface, a charged ionosphere and cosmic ray ionization. Despite its ubiquity, no fair weather electricity effect on clouds has been hitherto demonstrated. Here we report surface measurements of radiation emitted and scattered by extensive thin continental cloud, which, after \( \sim 2 \) min delay, shows changes closely following the fair weather electric field. For typical fluctuations in the fair weather electric field, changes of about 10% are subsequently induced in the diffuse short-wave radiation. These observations are consistent with enhanced production of large cloud droplets from charging at layer cloud edges.

Keywords: aerosol, droplet, charge, cosmic rays

1. Introduction
The existence of an atmospheric electric field in fair weather\(^1\) has been known for over two centuries [1–4] with its common universal time diurnal variation in clean air established globally by the Carnegie survey ship in the early 1900s [5, 6]. Any role for fair weather electricity in atmospheric processes, and clouds in particular, has, however, never been demonstrated. Classical meteorological investigations speculated on electrostatics as a factor in cloud development [7, 8] but, more recently, fair weather atmospheric electricity has been suggested as a physical ‘missing link’ coupling solar activity with climate [9–11]. Physical mechanisms linking fair weather fields with clouds therefore deserve further investigation.

Upper and lower edges of layer clouds are sensitive to fair weather electrification [12], as this is where the air conductivity drops substantially between the clear and cloudy air due to ion removal [13], and droplet charging results [14, 15]. The vertical fair weather current, from which the fair weather field originates, passes through the cloud edge conductivity boundary. At a sharp cloud boundary, the fair weather current can cause appreciable charging [16]. Using radiation measurements made beneath an extensive layer cloud, changes in cloud properties have been observed to occur shortly after fair weather electric field fluctuations, consistent with charge-induced changes in droplet properties.

2. Cloud droplet formation
Formation of cloud droplets requires a water vapour supersaturated environment and particles able to act as cloud condensation nuclei (CCN). In regions with supersaturation greater than the critical supersaturation (typically 1–2% above 100% relative humidity), a condensing droplet will grow, but in regions having insufficient supersaturation, the droplet will evaporate [17]. After condensation, droplets grow by vapour diffusion and droplet–droplet collision (coalescence), the latter providing more rapid growth as droplet size increases. Both condensation and coalescence can be influenced by charge [18]. Condensation can be facilitated at lower supersaturations if the condensation nucleus concerned is sufficiently highly charged to reduce evaporation [16]; coalescence to large droplets is enhanced by electric forces between charged droplets [19], which, because of electrostatic image forces, are always attractive at small separations whatever the relative polarities of the colliding particles [20].

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\(^1\) ‘Fair weather’ is used in atmospheric electricity to describe situations in which there is no strong local charge generation. It extends from serene sunny conditions with, formally, no weather, to overcast but non-convective non-raining or non-foggy conditions.
Fair weather droplet charging should occur at the edges of all liquid layer clouds, but, as small droplets generally co-exist with drizzle and rain, electrically-induced changes at the smallest droplet sizes will usually be obscured. To observe electrically-enhanced growth effects, the cloud droplet distribution needs to be dominated by small droplets. Thin, extensive layer clouds can provide a suitably narrow droplet distribution, biased towards small droplet sizes [21], with fair weather droplet charging occurring at the upper and lower cloud boundaries.

Two responses will occur from droplet number and droplet size changes. Firstly, in response to increasing the droplet number concentration, more scattering of incident solar radiation will occur, which will increase the diffuse short-wave radiation (\(S_d\)) at the surface. Secondly, for a thin cloud, the long-wave emissivity decreases slightly with droplet size (at \(\sim -0.1\%\) per 0.05 \(\mu m\) increase in effective radius) [21], hence a small charge-enhanced increase in the droplet size distribution will slightly reduce the emitted downward long-wave radiation (\(L_W_d\)). Increased droplet charging at the lower edge of a thin cloud can therefore lead rapidly to both an appreciable \(S_d\) increase and a small \(L_W_d\) decrease.

As well as the short-wave and long-wave surface radiation cloud responses, the initiating atmospheric electricity changes at the cloud can be detected at the surface. In fair weather conditions, the surface electric field, conventionally measured as the potential gradient (PG), is related to the global circuit vertical current density \(J_c\) by

\[
J_c = -\sigma F, 
\]

where \(F\) is the PG and \(\sigma\) the air conductivity [14]. At the upper and lower cloud boundaries, the space charge density \(\rho\) is

\[
\rho = -\varepsilon J_c \frac{d}{dz} \left( \frac{1}{\sigma} \right),
\]

where \(\varepsilon\) is the permittivity and \(\sigma\) varies with height \(z\) across the cloud–air boundary [12, 16]. For constant surface air conductivity, PG variations are therefore directly linked to variations in \(\rho\) at the cloud through equations (1) and (2). Conductivity changes across the cloud boundary are typically a factor of ten.

3. Stratiform cloud case study

3.1. Circumstances

Radiative and electrical changes are studied here for an extensive thin cloud layer, formed in continental air during anticyclonic weather in February 2008. The cloud advanced across the UK from the North Sea, persisting over the southern UK on the 14th February, and for part of the 15th February. At Nottingham (53.00° N, 1.25° W), the routine meteorological balloon sounding at 12 UT on 14th February passed through the cloud, showing a single layer about 300 m thick, with its base at about 350 m. The meteorological lidar and radar at Chilbolton (51.145° N, 1.439° W) determined the cloud base at about 300 m, with a layer thickness of about 200 m. In addition, the weak radar returns showed that large drops were absent \(^3\), suggesting circumstances in which coalescence or condensation processes might be directly observed.

Figure 1(a) shows the cloud over the southern UK on 14th February, observed by the MODIS satellite. Figures 1(b) and (c) show time series of surface radiation, wind and PG measurements, beneath the cloud at Reading (51.442° N, 0.938° W) for the 13th, 14th and 15th February. Figure 1(b) shows the surface broadband short-wave and long-wave radiative fluxes. The clear conditions on 13th February are apparent from the diurnal cycle evident in the global solar

\(^2\) http://weather.uwyo.edu/upperair/sounding.html

\(^3\) http://www.met.rdg.ac.uk/radar/cgi-bin/cloudarchive.cgi?date=20080214
irradiance ($S_d$), and the small diffuse solar irradiance ($S_g$); on the 14th February, however, there was a much reduced diurnal cycle in $S_g$, with fully overcast conditions causing the short-wave radiation to be entirely diffuse ($S_g = S_d$). There was also negligible diurnal variation in the downward long-wave radiation ($LW_d$) on the 14th February. Figure 1(c) shows the wind speed at 10 m ($u_{10}$), typical of steady local conditions. Appreciable, but not exceptional, high frequency variability was apparent in the PG, unlikely to be of local origin because of the quiescent conditions.

3.2. Analysis

Figure 2 shows a portion of the Reading PG data on 14th February, together with the $LW_d$ (figure 2(a)) and $S_d$ (figure 2(b)) measured beneath the cloud. Both figures show common variations in the PG, $S_d$ and $LW_d$, which occurred for over 8 h on the 14th and 15th February. Figures 2(c) and (d) present the same data portions after high pass filtering, retaining variations with timescales of less than 1 h. A correlation is clearly evident between the filtered PG and $S_d$ or $LW_d$. The possibility of an instrumentation cause can be rejected as additional sensors (for $S_d$, $LW_u$, net radiation $R_n$, and soil heat flux $G$) operating at the site used identical electronics [22] and the same logging system as for $S_d$ and $LW_d$. In these additional measurements (not shown), both the $S_d$ and $R_n$ data were dominated by the diffuse short-wave radiation and were also correlated with the PG, but $G$ and $LW_u$, which vary slowly because of damping effects of the soil, were not. The effect was therefore radiative, originating in the lower atmosphere.

The filtered data suggest a cloud response after the atmospheric electricity changes, as the PG changes generally occur before the radiative changes. Figure 3 demonstrates this lag effect at higher temporal resolution, using 20 s averages of the filtered data, through the use of compositing. ‘Compositing’ averages together data obtained either side of a defined event, allowing the mean behaviour in response to many such events to emerge from the natural variability. (This variability usually obscures the effects around a single event.) Here, the $LW_d$ and $S_d$ data are composited around local PG extrema to investigate the radiative response to PG changes, using data during the steady daytime conditions from 10 UT to 1530 UT with timescales longer than 2 h removed.

The compositing reveals both a significant $S_d$ increase and $LW_d$ decrease 1–2 min after a PG increase. If a PG increase were followed by an increase in droplet size and/or number around the cloud base, such an increase in $S_d$ and decrease in $LW_d$ would be a consequence. Proportionality between PG change and the sub-cloud radiative changes, allowing for a lag of 100 s, is summarized in the scatter plots in the lower panels of figure 3. For the averaged PG increase of 40 V m$^{-1}$ ($\sim$25% of the mean), the subsequent $S_d$ change was 6 W m$^{-2}$ ($\sim$10%) and the $LW_d$ change was $\sim$0.3 W m$^{-2}$ ($\sim$0.1%).

The lag in the radiative response cannot arise from instrument response times as these are much shorter than the observed lag$^5$.

$^4$ ‘Compositing’ is sometimes also known as a ‘superposed epoch’ analysis.

$^5$ All the instruments were continuously sampled at 1 Hz and 12 bit resolution. Specifically, the short-wave and long-wave radiation measurements were made using Kipp & Zonen CMP11 and CNR1 radiometers respectively, with a solar tracker and shade ball used to occult the short-wave radiometer for the $S_d$ measurement. The PG was recorded with a Chubb Instruments JCI131 field mill. The radiometers’ specified 95% time responses are 5 s (CMP11) and 18 s (CNR1), and the $\sim$3 dB cut-off frequency for the JCI131 is 7 Hz. Thus the PG response is effectively instantaneous with 1 Hz sampling, and, for averaging periods of 20 s or more, the radiometer response time effects will be small. In any case, both radiometers will respond several times more rapidly than the atmospheric lag time of $\sim$100 s observed.
Figure 3. Composites of differences formed on local maxima and minima of the potential gradient (PG), for PG, downward long-wave radiation ($LW_d$) and diffuse short-wave radiation ($S_d$), normalized in each case to one standard deviation of the quantity concerned; maxima in the composites correspond to 6.6σ (PG), 4.4σ ($LW_d$) and 4.6σ ($S_d$) respectively. Lower panels show PG-$S_d$ and PG-$LW_d$ scatter plots at 100 s lag. (Values are 20 s averages during 10 UT to 1530 UT on 14th February, high pass filtered to remove fluctuations longer than 2 h.)

The observed lag is unlikely to be the result of a geometric effect in which the radiation instruments sample downstream clouds whilst the field mill samples directly overhead. A simultaneous measurement of the direct solar beam ($S_b$) was also made using a Kipp & Zonen CH1 pyrheliometer (5° view angle, 7 s time response to 95%) mounted on the solar tracker. During overcast conditions this samples the cloud close to the sun’s position, where there is spatial anisotropy in the diffuse radiation source. No evidence for a lag effect in this region of the sky was found in the $S_b$ data, and negligible variability was apparent in $S_b$ compared with that present in $S_d$. Furthermore, for this alternative explanation that the PG and $S_d$ modulation were simply due to propagating cloud thickness changes, there would be an inverse relation between PG and $S_d$, which is the opposite of that observed.

4. Conclusions

These observations provide evidence of a direct effect of global atmospheric electricity on clouds. Because of the global presence of the fair weather current, similar effects may occur more generally in layer clouds. For typical variations in global fair weather current, the resulting change in thin clouds would correspond to the 6 W m$^{-2}$ found here, which would affect the atmosphere’s local radiative balance. Our results also provide evidence for charge-induced cloud microphysics, for example aiding coalescence [19] to larger raindrops. The initiation of raindrop coalescence remains an unsolved problem in cloud physics [23].

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Figure 1(a) was obtained by the NERC Satellite Receiving Station, Dundee University, Scotland.

References

[1] Beccaria G 1775 Della Eletricithe Terrestre Atmosferica e Cielo Serno Turin
[2] Aplin K L, Harrison R G and Rycroft M J 2008 Investigating earth’s atmospheric electricity: a role model for planetary studies Space Sci. Rev. 137 11–27

6 http://www.sat.dundee.ac.uk/
[3] Harrison R G 2004 Long term measurements of the global atmospheric electric circuit at Eskdalemuir Scotland, 1911–1981 Atmos. Res. 70 1–19

[4] Harrison R G and Ingram W J 2005 Air–earth current measurements at Kew, London 1909–1979 Atmos. Res. 76 49–64

[5] Isræl H 1973 Atmospheric Electricity vol 2 Fields, Charges, Currents (Problems of Cosmic Physics vol 29) (Jerusalem: Israel Program for Scientific Translations)

[6] Rycroft M J, Israelsson S and Price C 2000 The global atmospheric electric circuit, solar activity and climate change J. Atmos. Sol.-Terr. Phys. 62 1563–76

[7] Howard L 1837 Seven Lectures on Meteorology (Pontefract: James Lucas)

[8] Day J A and Ludlam F H 1972 Luke Howard and his clouds: a contribution to the early history of cloud physics Weather 27 449–61

[9] Dickinson R E 1975 Solar variability and the lower atmosphere Bull. Am. Meteorol. Soc. 56 1240

[10] Tinsley B A, Brown G M and Scherrer P H 1989 Solar variability influences on weather and climate: possible connections through cosmic ray-fluxes and storm intensification J. Geophys. Res. 94 14783–92

[11] Harrison R G and Carslaw K S 2003 Ion-aerosol-cloud processes in the lower atmosphere Rev. Geophys. 41 1012

[12] Zhou L and Tinsley B A 2007 Production of space charge at the boundaries of layer clouds J. Geophys. Res. 112 D111203

[13] Lihavainen H, Komppula M, Kerminen V-M, Järvinen H, Viisanen Y, Lehtinen K, Vana M and Kulmala M 2007 Size distributions of atmospheric ions inside clouds and in cloud-free air at a remote continental site Boreal Environ. Res. 12 337–44

[14] Chalmers J A 1967 Atmospheric Electricity 2nd edn (Oxford: Pergamon)

[15] Gunn R 1965 The hyper electrification of raindrops by electric fields J. Meteorol. 13 283–8

[16] Harrison R G and Ambaum M H P 2008 Enhancement of cloud formation by droplet charging, Proc. R. Soc. A 464 2561–73

[17] Mason B J 1971 The Physics of Clouds (Oxford: Pergamon)

[18] Pruppacher H R and Klett J D 1997 Microphysics of Clouds and Precipitation 2nd edn (New York: Kluwer Academic)

[19] Khain A, Arkhipov V, Pinsky M, Feldman Y and Ryabov Y 2004 Rain enhancement and fog elimination by seeding with charged droplets. Part I: theory and numerical simulations J. Appl. Meteorol. 43 1513–29

[20] Tinsley B A, Rohrbaugh R P, Hei M and Beard K V 2000 Effects of image charges on the scavenging of aerosol particles by cloud droplets and on droplet charging and possible ice nucleation processes J. Atmos. Sci. 57 2118–34

[21] Garrett T J, Radke I F and Hobbs P V 2002 Aerosol effects on cloud emissivity and surface longwave heating in the Arctic J. Atmos. Sci. 59 769–78

[22] Harrison R G and Knight J R 2006 Thermopile radiometer signal conditioning for surface atmospheric radiation measurements Rev. Sci. Instrum. 77 116105

[23] Kostinski A B and Shaw R A 2005 Fluctuations and luck in droplet growth by coalescence Bull. Am. Meteorol. Soc. 86 235–44