Charge measurements in stratiform cloud from a balloon based sensor

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Abstract. The electrification of stratiform clouds has is little investigated in comparison with thunderstorms and fair weather atmospheric electricity. Theory indicates that, at the upper and lower horizontal boundaries of layer clouds, charging will arise from vertical flow of cosmogenic ions in the global atmospheric electric circuit. Charge is transferred to droplets and particles, affecting cloud microphysical processes such as collision and droplet activation. Due to the lack of in-situ measurements, the magnitude and distribution of charge in stratiform clouds is not well known. A sensitive, inexpensive, balloon borne charge sensor has been developed to make in-situ measurements of edge charging in stratiform cloud using a standard meteorological radiosonde system. The charge sensor has now been flown through over 20 stratiform clouds and frequently detected charge up to 200 pC m$^{-3}$ near cloud edges. These results are compared with measurements from the same sensor used to investigate charge in particle layers, such as volcanic ash from the Eyjafjallajökull eruption, and Saharan dust in the Cape Verde Isles.

1. Introduction
Although most previous research into cloud electrification has been concerned with thunderstorms, other cloud types can also be electrified. Stratiform clouds in particular are thought to be charged as theory predicts that the upper and lower boundaries of these clouds should become charged through vertical current flow in the global atmospheric electric circuit [1]. Cloud droplets and aerosol particles in these regions will become charged, for which implications are expected in cloud microphysical processes, particularly in respect to collision and scavenging processes (e.g. [2]-[4]). However, very few electrical measurements have been made in-situ in stratiform clouds, and consequently very little is known about the magnitude of the charge.
2. Charge generation on stratiform cloud edges

2.1. Theory

The electrical characteristics of Earth’s atmosphere are conveniently summarised in the conceptual framework of the Global Electric Circuit, GEC [5]. In the GEC, a vertical conduction current, $J_c$, flows between the ionosphere and Earth’s surface, as a result of the large difference in potential between these two regions. $J_c$ is typically considered in terms of the fair weather atmosphere (i.e. no clouds or significant weather), however in the presence of cloud, $J_c$ is predicted to charge the upper and lower edges of stratiform clouds of large horizontal extent. This occurs due to the gradient in conductivity, $\sigma_t$, between the high conductivity clear air outside the cloud, and the low conductivity air inside the cloud (due to ion-droplet attachment). The space charge, $\rho$, predicted to occur at the upper and lower cloud edges is given by Gauss’ law,

$$\rho = \varepsilon_0 J_c \frac{d}{dz} \left( \frac{1}{\sigma_t} \right)$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ F m$^{-1}$, $z$ is vertical distance, $d/dz (1/\sigma_t)$ is the vertical gradient in conductivity, and both $z$ and $J_c$ are positive downwards. The vertical conductivity gradient near stratiform cloud edges is therefore associated with a positive layer of space charge at cloud tops (resistivity $(1/\sigma_t)$ increasing in the direction of positive $z$ and $J_c$) and negative charge at cloud base.

2.2. Instrumentation

To measure stratiform cloud charging in-situ, a Cloud Edge Charge Detector (CECD) has been specially developed for use on weather balloons [6]. The CECD consists of a spherical electrode, connected to a sensitive electrometer which measures the voltage on the electrode. Changes in the electrode voltage result from the presence of charge, via induction and impaction effects. The CECD electrode voltage is reset every 60 seconds to prevent prolonged saturation of the electrometer in highly charged areas. The CECD flies alongside a standard meteorological radiosonde which measures pressure, temperature, relative humidity, and GPS position. A specially developed data acquisition system, similar to the one described in [7], is used to transmit the CECD data over the radio link of the radiosonde, synchronous with the meteorological data. Measurements are made at 1Hz, giving a typical vertical sampling resolution of 5m (for a 5ms$^{-1}$ ascent rate).

2.3. Measurements

The CECD has been flown on over twenty balloon flights through stratiform cloud from a variety of locations around the UK. Figure 1 shows results from one of these flights, at the base of an extensive layer of stratocumulus cloud over the Southern UK. Figure 1(a) shows cloud droplet number concentration, (b) the voltage on the CECD electrode as it descended through the cloud layer, and (c) the resulting space charge (derived from the rate of change of CECD electrode voltage and ascent rate [6]. The cloud base is at ~3.30km, where the cloud droplet number concentration (and thus the air conductivity) begins to change. This is also the region where the CECD voltage changes, denoting the presence of space charge.

From the small sample of stratiform clouds performed during this study, it has been found that the majority of stratiform cloud edges (two-thirds of those measured) are charged, with typical mean charges of ~20pC m$^{-3}$ and maximum charges of ~200pC m$^{-3}$. In addition, a case study of the CECD flight detailed in Figure 1. shows that the measured cloud edge space charge agrees closely with that expected from theory [8], supporting the hypothesis of charging from the vertical conduction current.
Figure 1(a) Vertical profile of cloud droplet number concentration through an extensive layer of stratocumulus cloud, measured by a Cloud Droplet Probe on the FAAM research aircraft, flying on the same day. (b) CECD electrode voltage measured on radiosonde descent through the same cloud layer. (c) Magnitude of space charge derived from rate of change of CECD electrode voltage and sonde ascent rate. Adapted from [8].

3. Charge associated with other atmospheric phenomena

Space charge is separated whenever there is a gradient in conductivity, such as at boundaries between clear and droplet/particle laden air, therefore charging by this mechanism is expected to occur in stratified dust and pollution layers, as well as in stratiform cloud. The CECD has thus been used to investigate charging in volcanic plumes and Saharan dust layers, in which charging may partly arise by this mechanism. During flights though ash and dust the CECD was flown alongside a specially developed aerosol particle counter [9], which measures particles of diameter 0.6 to 10.6 μm using a light scattering method. Results from flights through a volcanic ash plume and elevated Saharan dust layer will be described in subsequent sections.

3.1. Volcanic ash plume charging

Radiosondes are well suited to making measurements in areas that are hazardous to manned aircraft, hence the CECD and aerosol particle counter were used to sample the Eyjafjallajokull volcanic ash plume during the flight ban in April 2010 [10]. A layer of positively charged ash of ~0.5 pC m\(^{-3}\) was detected between 3.8 and 4.5 km on a sounding made from Stranraer, Scotland on 19\(^{th}\) April. Possible explanations for the charge generation include charging at the eruption site - volcanic lightning was observed on 17\(^{th}\) April, when the plume was emitted from the volcano - however charge decay considerations suggest that any residual charge from the eruption should have decayed within 10 km of the vent (Stranraer is ~1200 km from the eruption site). A second explanation is charging of the upper and lower edges of the plume from vertical current flow in the GEC as described in section 2.1, however the observed charging was not confined to the plume edges, and was unipolar, suggesting an additional charge generation mechanism.

3.2. Saharan dust layer charging

Several balloon measurements in elevated layers of dust were made from the Cape Verde Isles, ~600 km off the west coast of Africa, which experience frequent Saharan dust outbreaks. Two balloon soundings instrumented with the aerosol particle counter and CECD detected dust particles up to 4 km altitude, with increased levels of charge inside the dust layers. Charges of up to 25 pC m\(^{-3}\) were detected inside the dust layers, which, like the charges observed in the volcanic ash plume, are not
expected and again suggest that a continuous charge generation mechanism is present. Charge
generation during the initial dust lofting stage is likely to occur due to particle-particle collisions and
collisions with the surface, however, the large distances between the lofting region and measurement
site suggest that this mechanism cannot account for the observed charging. Edge charging of dust
layers, from vertical current flow through the layers provides an alternative generation mechanism,
however, modelling the space charge on the layer edges produces charges two orders of magnitude
smaller than those observed.

4. Conclusions
Theory predicts that charge should be generated at the boundaries between clear and droplet/particle
laden air, due to flow of the vertical conduction current in the Global Electric Circuit. Such charge
layers have been observed at the upper and lower edges of stratiform clouds by a specially developed
balloon borne charge sensor. The sensor has also detected small amounts of charge in volcanic ash
plumes, and Saharan dust layers far from their point of origin [11]. In the stratiform cloud case, the
measured charges agree with that predicted by edge charging theory via the conduction current,
however this is not so in the volcanic ash and Saharan dust layer cases, suggesting the presence of
additional charge generation mechanisms, which are, at present, incompletely understood.

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