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Self-charging of the Eyjafjallajökull volcanic ash plume

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Abstract
Volcanic plumes generate lightning from the electrification of plume particles. Volcanic plume charging at over 1200 km from its source was observed from *in situ* balloon sampling of the April 2010 Eyjafjallajökull plume over Scotland. Whilst upper and lower edge charging of a horizontal plume is expected from fair weather atmospheric electricity, the plume over Scotland showed sustained positive charge well beneath the upper plume edge. At these distances from the source, the charging cannot be a remnant of the eruption itself because of charge relaxation in the finite conductivity of atmospheric air.

Keywords: atmospheric electricity, aerosol, radiosonde, lightning

1. Introduction

Electrification of volcanic plumes provides a spectacular source of lightning [1, 2]. Volcanic lightning can facilitate remote sensing [3] of an active eruption, from which aircraft can be warned of hazards from volcanic ash clouds [1]. Volcanic plume electrification has previously been investigated using surface measurements of charged sedimenting particles [4] and below-plume surface determinations of atmospheric electric fields [5]. Observations [1] of volcanic particle charging have previously been made up to 200 km from the vent [6].

The eruption of the Icelandic volcano Eyjafjallajökull (63.63°N, 19.62°W, 1666 m a.s.l), which began on 20 March 2010 provided an opportunity to study plume electrical properties over Europe, far from its source. The eruption initially produced lava fountains on 21 March, ejected from a 500 m long fissure. The activity was dominated by fissure-fed lava fountains and basaltic lava flows until late 13/14 April, when new vents opened on the southern rim of the central caldera, capped by the glacier. This resulted in an ash (∼58% SiO_2)[4] plume rising to more than 8 km altitude being blown eastwards, with tephra-fall being reported in SE Iceland. The eruption plume reached mainland Europe on 15 April, causing substantial airspace closure[5]. During this long range plume transit, any remnant particle charge generated during the eruption itself would have dissipated, due to typical atmospheric charge relaxation times [1] of order 100–1000 s. *In situ* charge measurements of the Eyjafjallajökull eruption plume over western Scotland on 19 April are reported here, using a balloon-carried package combining charge and aerosol particle sensors [7].

2. Methodology

The instrument package was designed to determine the plume's electrical properties and particle size distribution separately, using the data telemetry of a standard meteorological radiosonde. Plume particle size distribution was found by pumping air through an optical particle counter (OPC) and the electrical properties by a relaxation probe technique.

The OPC used scattered light to find the particle concentration from the rate of detected pulses, and the particle size is retrieved from the pulse height in bins with mean particle diameters of 1, 2, 4 and 8 μm, and >10.4 μm diameter for the largest bin. Electrical plume properties were

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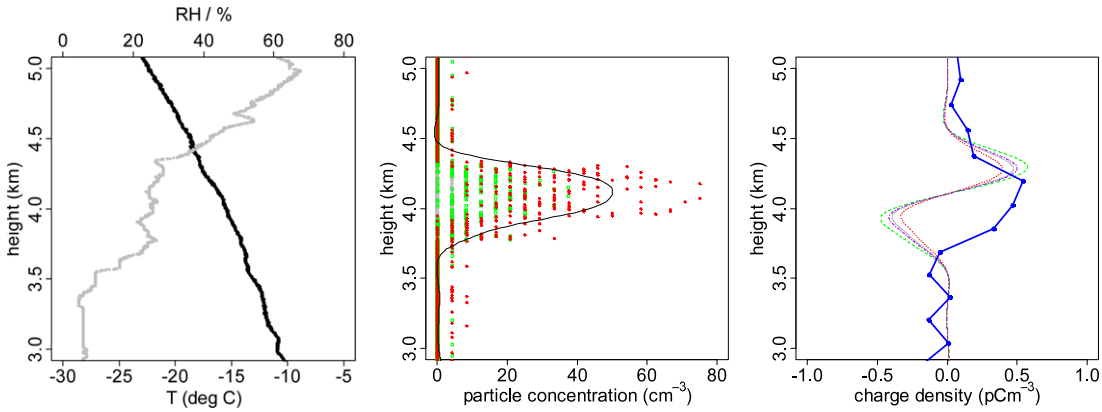

Figure 1. (a) Meteorological sounding (temperature (black) and relative humidity (grey)) made on 19 April 2010 from Stranraer, Scotland. (b) Plume particle concentrations for bins of different diameter d: 0.6–1.4 μm red circles, 1.4–2.6 μm green squares and $d > 2.6$ μm grey diamonds, with fitted smoothing spline (solid line) for the total particle concentration. (c) Measured charge density (blue points with thick solid line) and calculated charge density for assumed background aerosol diameter and concentrations of (0.1 μm, 1500 cm^{-3}) solid grey, (0.4 μm, 1500 cm^{-3}) dotted green, (0.1 μm, 500 cm^{-3}) dashed red and (0.4 μm, 500 cm^{-3}) dot-dashed purple.

determined from the voltage on a 12 mm diameter spherical electrode exposed at the side of the package, connected to an electrometer voltmeter [8] circuit. The electrode voltage was reset to 4 V every 60 s, and the local charge determined from the rate of increase or decrease of electrode voltage and the ascent rate of the sensor [9], the latter derived from successive atmosphere pressure measurements. Similar aerosol and charge sensors have previously been calibrated in the laboratory, by introducing standard aerosol particles and by applying electric field changes [10] respectively.

3. Results

Based on Met Office projections of the plume transport from the Icelandic source, the balloon instrument package was launched from West Freugh, near Stranraer, Scotland (54.86°N, 4.94°W), at 0830UT on 19 April 2010, into mostly cloud-free fair weather conditions. The balloon intercepted the plume base at 3.7 km aloft, 9 km south east of the launch site. Air temperature at the plume base was −14 °C, with relative humidity (RH) <25% (figure 1(a)). The RH remained low to the top of the plume at 4.3 km, which precludes confusion with cloud.

Figure 1(b) summarizes the measured particle size profile which exhibits a layered horizontal structure, in which most plume particles had diameters less than 2.6 μm. Using the mean aerosol diameter (1.4 μm) and maximum total particle concentration (100 cm^{-3}), the charge relaxation time calculated using the ion–aerosol attachment coefficient [11] is 433 s. Although ion–aerosol attachment coefficients have conventionally been derived for spherical particles or droplets, the irregular shape of volcanic ash particles is likely to increase the particles' effective ion capture area. This will act to increase the ion–aerosol capture rate, reducing the relaxation time from the estimate given above. Hence, assuming steady plume properties, these considerations indicate that any initial eruption charging would have decayed within about 10 km of the vent for horizontal transport speeds of 10 m s^{-1}, i.e. well before the plume arrived at the measurement site. (Back-trajectory calculations allow the plume to be aged as then 32 h old, emitted originally as ash around 00UT on 17 April, during a lightning active phase.)

Plume charge was found from the electrical sensor data every 60 s (∼200 m height resolution), using a linear fit to the electrode voltage values, from which the rate of change of voltage was determined and the clean air rate of change subtracted. Using the laboratory calibration of electrode capacitance, the charge exchanged between the plume particles and the sensor by impaction was found. These measured values have been added to figure 1(c). The vertical charge structure shows some similarities with the vertical concentration profile, particularly that of the smallest diameter particles.

4. Analysis

Beyond the initial eruption charging, further charging is expected to develop at the upper and lower edges [12] of a horizontal plume from the vertical electric current flow [13] sustained in the fair weather atmosphere by the global atmospheric electrical circuit [14]. In these conditions plume edge charging results from current flow in the vertical air conductivity gradient at the plume–air boundary, where an electrical conductivity transition is established between the clean air (in which cosmic ray generated ions are removed only by their self-recombination) and the low conductivity air of the plume (in which ions are scavenged by plume particles). The vertical conductivity gradient is associated with a vertical gradient in the electric field E_z in the same region, by Gauss' law. The vertical electric field gradient $\mathrm{d}E_z/\mathrm{d}z$ and charge density ρ are related by

$$\frac{\mathrm{d}E_z}{\mathrm{d}z} = -\frac{\rho}{\varepsilon_0}, \tag{1}$$

where ε_0 is the permittivity of free space. Assuming Ohm's law ($J_c = \sigma E$, for air conductivity σ), the charge density is [15]

$$\rho = -\varepsilon_0 J_c \frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{1}{\sigma}\right) = \varepsilon_0 J_c \left(\frac{1}{\sigma^2}\right)\frac{\mathrm{d}\sigma}{\mathrm{d}z} \tag{2}$$

where J_c is the fair weather vertical current density which is constant with height z.

To estimate the plume edge charge, the vertical variation in σ has been calculated from the steady-state ion balance equation [16] using interpolating splines fitted to the measured plume particle size and concentration, shown for the particle concentration in figure 1(b). For the ion balance equation calculation, ion mobility of $\mu = 1.7 \times 10^{-4}$ m^2 V^{-1} s^{-1}, ion–ion recombination coefficient $\alpha = 1.6 \times 10^{-12}$ m^3 s^{-1} were assumed [16], with ion–particle attachment coefficients calculated for neutral particles of the local interpolated diameter and an ion production rate [17] of 4 cm^{-3} s^{-1}. To estimate the conductivity gradient at the plume edge, a background clean air aerosol concentration away from the plume is required. This does not depend sensitively on the background aerosol concentration, which has been investigated using a range of monodisperse sizes and concentrations, assuming sizes smaller than the minimum detection size of the optical particle counter. The calculated edge charge from this method is shown in figure 1(c), for a typical conduction current density, $J_c = 2$ pA m^{-2} [18] and a range of background aerosol properties. Spline smoothing emphasizes the dominant region of edge charging over other smaller concentration fluctuations within the plume, but the sensitivity of the calculated edge charge magnitude to this or the other parameters assumed does not affect the derived edge charge's location.

It is clear from figure 1(c) that the charge measured differs in its vertical profile from that predicted theoretically, whatever the background aerosol assumptions made. The charge is not solely associated with the sharp upper plume edge, but also well beneath it within the plume. Because the measured charge extends down below the predicted upper edge charge region, from which micron size particles will sediment only slowly ($\ll$1 cm s^{-1}) compared with the charge relaxation time ($\sim$100 s), it is inferred that the more extensive charge region observed arises from particle–particle interactions within the plume.

An upper constraint for the individual particle charge can be estimated from the maximum charge observed, 0.54 pC m^{-3} (3.4×10^6 elementary charges m^{-3}), at 4.2 km altitude where the plume contained 4.65×10^7 m^{-3} particles larger than 0.6 μm, of mean diameter 1.4 μm. Because of the small projected horizontal collection area (1.1×10^{-4} m^2) of the rising sampling electrode, only a fraction of those particles would be intercepted. The number intercepted is estimated from the volume swept out vertically as the electrode rises unit distance, i.e. $\sim$5300 particles. Evenly partitioning the maximum measured charge density across these intercepted particles leads to about 600 elementary charges per particle ($\sim 10^{-3}$ C kg^{-1}). If, as is likely, the particle interception is more efficient than the conservative geometrical estimate used because of electrode and particle motions, the particle charge would be smaller, but triboelectric charging up to 10^{-3} C kg^{-1} has been reported [2].

Several mechanisms [1, 2] have been proposed to explain the substantial electrification necessary to generate volcanic lightning, which may be relevant considerations in explaining the charging observed. These include electrification associated with plume formation (fractoemission or boiling), thundercloud-like charging, and radioactive decay. Of these, the energetic processes associated with plume formation can be rejected at such large distances from the vent, and the thundercloud-like charging also seems unlikely because of the low relative humidity measured in the plume. The unipolar nature of particle charge observed is known to be characteristic of radioactive charging [19], but there is no further evidence to support this possibility.

5. Discussion

These findings demonstrate that charge exists well within a volcanic plume, the origin of which is not readily attributable either to the eruption directly or subsequent fair weather charging. In general, particle charging will modify vertical deposition speeds in the fair weather atmospheric electric field [20] and modify particle–particle agglomeration rates and particle wet removal by droplets [16, 21]. Charged particles can cause aircraft radio interference [22] and, if introduced into aircraft cabins, charged ash may present an electrostatic hazard to occupants or aircraft systems.

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