Observations of the atmospheric electric field during two case studies of boundary layer processes

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Abstract

We present measurements of potential gradient (PG) with associated meteorological variables and cloud profiles for two examples of convective boundary layer processes. Aerosol acts as a tracer layer to show lofting of the convective boundary layer; the rising aerosol layer results in a decrease in PG. In foggy conditions, the PG is seen to increase during the fog and then reduce as the fog lifts, as expected.

Keywords: atmospheric electric field, boundary layer

1. Introduction

The global atmospheric electric circuit is driven by global thunderstorms and shower clouds separating charge between Earth’s surface and the ionosphere [1]. The atmosphere is weakly conductive which permits a current to flow; this results in a vertical electric field given by

\[ E = \frac{J_c}{\sigma} \]  

where \( J_c \) is the air–Earth conduction current density and \( \sigma \) is the electrical conductivity of the air. By convention the potential gradient (PG) is recorded, which is the negative of the electric field. PG is sensitive to changes in the local atmospheric conditions, which produce either a change of air conductivity or the amount of charge. Fair weather conditions show positive PG, usually below 300 \( \text{V m}^{-1} \) [2], and low variability in PG.

Increasing the conductivity of the air will decrease the potential gradient (PG) for a constant current. Such changes in conduction near Earth’s surface are usually due to changes in aerosol concentration. Condensation of water droplets as clouds or fog will decrease the local air conductivity, as will increased particulate pollution levels. The dependence of PG on aerosol concentration has been used with historical PG measurements to estimate pollution levels in the past (e.g. [3]).

Other examples of meteorological conditions affecting PG include shower clouds, wind direction and thunderstorms. Shower clouds have internal electrostatic structure [6] which affects the surface PG as the cloud passes. Nearby thunderstorms and lightning strokes will have a significant effect on the local PG. Changes in wind direction can affect the local aerosol concentration, affecting the PG [2].

In this letter we present measurements of the PG and relevant synoptic variables for two examples of convective boundary layer processes. For the first time, PG measurements were made in combination with cloud and low-level aerosol profiles measured with a co-located laser cloud base recorder (LCBR). These measurements clearly illustrate the convective boundary layer processes. Previous work has used timescales of boundary layer PG variability to infer their turbulent origins [4, 5] but in this work we exploit LCBR technology to qualify PG variability to overhead convective cloud, fog or other features observed with optical backscatter. These initial studies provide an indication of the association between different boundary layer processes and PG variability, but more sustained field campaigns will be required to confirm and quantify these relationships.

2. Methods

A Campbell Scientific CS110 Electric Field Meter is used to measure the vertical component of the PG at a height of 2 m above ground level at Met Office headquarters in Exeter, UK.
Figure 1. Meteorological measurements obtained during a convective day, 8 August 2011, Exeter, UK. (a) Shows the LCBR backscatter (colourbar) as a function of height (left axis) and PG (yellow solid line, right axis). Space charge builds up overnight and is then lofted as the convective boundary layer begins to rise. (b) Shows the air temperature (solid line) and the grass temperature (dotted line). A temperature inversion starts at 0630 UTC, shortly before the boundary layer begins to rise.

For this study, the measurement range is 0–2.2 kV m$^{-1}$ with resolution 0.32 V m$^{-1}$; the PG is measured every second. A co-located Jenoptik CHM15k-Nimbus LCBR provides backscatter measurements of cloud and aerosols every 30 s between 15 m and 15 km with vertical resolution of 15 m. Wet bulb, dry bulb and grass temperatures (electronic resistance thermometers are used for all temperature measurements), relative humidity (Rotronic Hygroclip) and visibility (Vaisala FD12P Present Weather Sensor) are all also measured at this site. All the instruments used in this study are located in a meteorological enclosure on a terrace set into a gently sloping south-facing slope. The Met Office building is approximately 40 m to the south of the enclosure and the enclosure is approximately 5 m lower than the Met Office roof level.

During periods of wind from the south or south-west, any space charge generated by the Met Office supercomputer cooling system is directed towards the enclosure.

3. Convective boundary layer

Figure 1(a) shows the potential gradient and the range-corrected LCBR backscatter measured at the Met Office, Exeter, on 8 August 2011. Space charge builds up during the night and is trapped by the temperature inversion, which acts as a lid to convective motion, shown by the grass and air temperatures in figure 1(b). A temperature inversion occurs when the temperature increases with height i.e. when the surface temperature is below that of the air temperature (in this case, measured 1.5 m above the surface). During these conditions a parcel of air at the surface will not be able to ascend by convective motion and the boundary layer will not be ventilated by convective motion. This build up of space charge under the temperature inversion results in a variable negative PG. The variability is likely to be due to shear turbulence around nearby obstacles.

Negative PG during fair weather conditions implies a nearby charge separation process producing negative space charge of sufficient strength to reverse the fair weather PG. The source of this space charge is suggested to be from either an evaporative cooling system approximately 40 m from the observation site, or trapping of natural radioactive substances (e.g. radon) under the nocturnal temperature inversion, creating a reversed electrode effect [7]. As the build up of space charge is not seen on every calm, stable night (as would be expected from radon produced in situ), the space charge is mostly likely to originate from the cooling system.

Mid-level shallow cloud is seen in LCBR backscatter between 0100 UTC and 0300 UTC. Previous observations indicate such clouds are not likely to be sufficiently charged to reverse the surface fair weather field; this type of field reversal is more commonly seen during the passage of relatively deep convective clouds [2].

Between 0630 UTC and 0800 UTC the inversion begins to break up, as shown by the diverging grass and air temperatures. The break up of the inversion corresponds with a decrease in PG. As the convective boundary layer begins to evolve, the trapped space charge is released and the PG decreases as the boundary layer rises. Periodic cycles
Figure 2. Meteorological measurements obtained during foggy conditions, 29 September 2011, Exeter, UK. (a) Shows the number of backscattered photons received at the LCBR (colourbar) as a function of height (left axis) and PG (yellow line, right axis) for a period of fog. The relative humidity (solid line, right axis) and visibility (dotted line, left axis) are shown in (b). The relative humidity decreases and the visibility increases as the fog begins to lift at 0900 UTC, after the PG has become more variable. The dry bulb (solid line) and wet bulb (dotted line) temperatures are shown in (c).

4. Fog

An increase in the number density of suspended water droplets (cloud or fog) decreases the electrical conductivity of the air by removal of small ions by attachment, which decreases the electrical conductivity of the air, therefore increasing the PG (equation (1)) [8, 9]. Figure 2(a) shows measurements of the PG and cloud profiles in Exeter for the morning of 29 September 2011. Visibility and relative humidity are shown in figure 2(b) and wet and dry bulb temperatures are shown in figure 2(c).

Figure 2(b) shows visibility decreasing steadily from midnight until it reaches a minimum at 0330 UTC, indicating that haze has turned to mist and then into fog; this coincides with a doubling of the PG. Backscatter returns from the LCBR show increasing presence of low cloud and fog above 20 m, but the increase in PG is seen slightly before the droplet density is large enough to create a measurable backscatter return, demonstrating the potential use of PG measurements for the prediction of fog formation. This increase in PG may be due to the swelling of hygroscopic nuclei as the relative humidity increase before fog formation, increasing the surface area for ion–aerosol attachment.

A reduction in the PG between 0400 UTC and 0500 UTC coincides with a temperature minimum. This could indicate either thinning of the mist or increased conductivity of the local atmosphere due to the ionizing effects of trapped radon gas.

From 0500 UTC onwards the PG increases, as does the relative humidity. Backscatter returns indicate the fog is becoming increasingly thick. The fog is at its densest at 0900 UTC before convective processes begin and the fog begins to lift, resulting in a drop in PG. As the fog and mist becomes increasingly inhomogeneous, the PG becomes more variable, representing the change in conductivity between mist and fog patches and clear air. The variability of the PG increases before the other instruments detect the fog to be lifting (i.e. increased visibility, decreased humidity, reduced LCBR backscatter). By midday the fog has lifted completely, visibility has increased to 20 km and the PG has returned to a fair weather value of 75 V m$^{-1}$. The spike in PG at 1100 UTC is due to exhaust gases from backup generators being tested nearby at this time.

5. Conclusions

We have presented co-located measurements of PG with LCBR backscatter for two examples of convective boundary
layer processes: shallow convection and radiation fog. Cloud and aerosol measurements from a co-located LCBR are used for the first time to illustrate the boundary layer processes affecting the near-surface electric field. PG measurements have been shown to complement other forms of boundary layer monitoring for the onset of convection following the erosion of a nocturnal inversion after sunrise, and for the formation, density and dissipation of fog. These case studies suggest that, following long-term measurements of PG during convective boundary layer processes, PG measurements at boundary layer monitoring sites could be used to improve forecasting of fog and convective boundary layer processes.

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