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Short communication

Smoke emissions from industrial western Scotland in 1859 inferred from Lord Kelvin's atmospheric electricity measurements

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A B S T R A C T

Lord Kelvin (William Thomson) made careful, calibrated measurements of the atmospheric Potential Gradient (PG) at three sites on the east side of Arran in 1859. The PG was always anomalously high in easterly and north-easterly winds. Positive space charge from sea spray may have contributed to the high PG at two coastal sites, but measurements made on Goatfell, inland and 100–175 m above sea level are unlikely to have been affected by spray. Instead, pollution from the Scottish mainland seems the more likely cause of the high PG at Goatfell, which varied from 300 to 1000 $\mathrm{Vm^{-1}}$ on 10th–11th October 1859, corresponding to smoke levels from 0.2 to 0.8 $\mathrm{mgm^{-3}}$. Gaussian plume calculations, based on the atmospheric conditions described by Lord Kelvin, and constrained by early Glaswegian pollution measurements, indicate a substantial source region located on the Scottish mainland, 20–40 km from Arran, emitting between 10–10^4 $\mathrm{kg\,s^{-1}}$.

1. Introduction

Historical smoke pollution can be retrieved from early atmospheric electricity measurements because of the substantial effect of smoke on air's electrical properties. For example, early atmospheric Potential Gradient (PG) measurements established by the Scottish physicist Lord Kelvin (William Thomson) at Kew Observatory, near London was used to estimate the local air pollution in 1863 as $0.17 \pm 0.05\ \mathrm{mg\,m^{-3}}$ (Harrison and Aplin, 2002).[1] This atmospheric electricity proxy technique exploits the reduction of air conductivity that results from the removal of air ions as they become attached to smoke particles. As the product of the PG and conductivity σ gives J, the air-earth current density J in the global electric circuit,

$$J = \sigma P \tag{1}$$

which is sustained by distant thunderstorms and is relatively constant (e.g. Chalmers, 1967), a local increase in PG will result from any smoke-induced decrease in air conductivity. Hence, in polluted air, the PG can greatly exceed the typical clean air values $\sim$120–160 $\mathrm{Vm^{-1}}$ (Chalmers, 1967). Using long-term co-located measurements of air conductivity, PG and smoke concentration at Kew Observatory, Harrison (2006) calibrated the PG to smoke, obtaining a sensitivity of 1082.6 $\mathrm{Vm^{-1}(/mg\,m^{-3})}$. The combination of PG and air conductivity measurements at Kew permitted calculation of a mean particle radius of 0.8 μm, implying that although sub-micron sized particles only comprise a small fraction of the "smoke" mass concentration, they contribute substantially to the air's electrical properties.

Prior to his installation of continuous PG recording apparatus at Kew in 1862, Kelvin developed the instrumentation techniques through investigations of the PG at a number of sites near to his laboratory in the University of Glasgow, including on the Isle of Arran, off the west coast of Scotland. Using a Gaussian plume model and the Harrison (2006) smoke calibration, the PG measurements on Arran are used here to estimate smoke pollution levels in Glasgow area in 1859. Such inferred historical pollution data can be used for social history, epidemiology, and assessment of historical black carbon loading for climate (e.g. Ramathan and Carmichael, 2008).

2. Kelvin's PG measurements on Arran

Lord Kelvin was a brilliant experimentalist, who developed several novel instruments for PG measurement. The general principle was that a potential equalizer (e.g. a flame or a water spray)

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[1] In comparison, black smoke concentrations in Central London in 2009 were $\sim 10\ \mathrm{\mu g\,m^{-3}}$ (http://uk-air.defra.gov.uk/, accessed December 2011).

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acquired the air's local potential, which was then determined using an electrometer connected to the equalizer. Kelvin's portable[2] electrometer, when used with a flame probe, allowed him to measure the PG beyond the fixed sites to which he was originally limited. This flexibility appears to have inspired him to measure the PG on the east coast of Arran, an island off the west coast of Scotland (Fig. 1), in 1859. His measurements were made close to the beach, 55 m away from Kelvin's house, Invergarry, at the island's main settlement, Brodick, and also on Goatfell, between 3.2 and 4 km from the house. Kelvin compared this roaming data to PG determined using the fixed (water dropper) electrometer system installed at his house. This electrometer was calibrated regularly against electrochemical battery standards, so that "13.25 to 14 degrees of torsion were required to bring the index to zero, when urged aside by the electromotive force of ten zinc-copper water cells." As the emf from one zinc-copper water cell is 1.08 V, the electrometer's sensitivity was 0.77–0.82 V per angular degree of torsion,[3] which remained stable for about three days after calibration. The portable electrometer was regularly compared to the house electrometer and to electrochemical cells to maintain its calibration, independently of the water dropper calibration. Fair weather results obtained at Arran with the portable electrometer were consistent with Kelvin's other Scottish measurements of clean air PG (e.g. at St. Andrews) of 133 $\mathrm{Vm^{-1}}$ (Thomson, 1859; Bennett and Harrison, 2007).

> "Observations with the portable electrometer had given, in ordinary fair weather, on the island of Arran, on a flat open sea beach, readings varying from 200 to 400 Daniell's elements, as the difference of potentials between the earth and the match, at a height of 9 feet above it." (Thomson, 1872)

In modern units, the Arran beach readings therefore correspond to typical fair weather, clean air PG variations of 80–158 $\mathrm{Vm^{-1}}$.

Kelvin noted that whenever the wind was from the east or north-east, the PG was a factor of 6–10 greater, 480–1580 $\mathrm{Vm^{-1}}$. This behaviour was so predictable that Kelvin could use the PG enhancement to detect a change in wind direction before the change could be identified using other techniques. Kelvin also observed that the PG was much more variable in these conditions, with enhanced variability particularly associated with a light east wind. One example is of the PG varying from 130–500 $\mathrm{Vm^{-1}}$ over a few minutes under an east wind, whereas a variation of 106–141 $\mathrm{Vm^{-1}}$ was more common over this timescale (Thomson, 1860). Contemporary data indicates that the PG is increased and variable when air is particle laden, for example when it is foggy (Bennett and Harrison, 2007; Harrison, 2011). However, Kelvin's detailed notes did not mention fog during any of these measurements, so other aerosol carried by an easterly wind seem a likely explanation. Two possible explanations will now be considered further: (1) Kelvin's own suggestion of sea spray and (2) particulate pollution from the Scottish landmass.

2.1. Effect of sea spray

Kelvin was aware that sea spray had an effect on the PG. In an easterly wind, the PG by the beach was typically 346 $\mathrm{Vm^{-1}}$ compared to 373 $\mathrm{Vm^{-1}}$ at the house, which was more sheltered from the sea. At the time Kelvin explained the reduction in PG by the negative effect of sea spray, solely on the basis that spray was seen to reach the beach instrument, but not the house sensor (Thomson, 1860). Kelvin subsequently used Lenard's findings that sea spray produced positive space charge to provide a different interpretation: that *all* the Arran high PG readings could be attributed to sea spray (Thomson, 1911). In this statement, Kelvin was acknowledging that his initial suggestion that sea spray reduced the beach PG was probably incorrect. With hindsight, the variability in Kelvin's measurements indicates that the beach and house readings were indistinguishable. Seventy years later, Blanchard (1966) confirmed that breaking sea spray produced positive space charge (through a different mechanism to Lenard), which enhanced the PG on the Hawaii coast.

Positive space charge carried by sea spray in an easterly wind remains a possible explanation for the enhancement in PG observed by Kelvin close to the coast, assuming that there was no detectable difference between PG measured at the beach and at the house. However, charged spray is unlikely to be transported sufficiently to also affect the Goatfell measurements, >2.5 km inland and 100–175 m above sea level, because after a few tens of seconds the droplet charge diminishes to a small, equilibrium, value due to atmospheric relaxation (Blanchard, 1963; Bennett and Harrison, 2006). The positive effect of sea spray almost certainly explains some of the enhanced beach PG regularly observed by Kelvin under fair weather conditions, so this data is not considered further. It is possible to develop an alternative explanation for the increased PG at Goatfell, based on transport of smoke pollution to Arran from the Scottish mainland.

3. Glasgow smoke pollution

The Glasgow conurbation had undergone a massive industrial expansion by the 1850s and evidence for its reputation as a polluted city exists in many sources. A Glaswegian hotelier even invented a filtration device to be placed over the mouth during the night to remove the worst of the smoke (Tyndall, 1871). The city's sandstone buildings, clean at the beginning of the 19th century, were covered with black soot fifty years later, and early measurements, from the early 1900s, indicated Glasgow's air pollution was comparable to London's (Thorsheim, 2006). A mid-nineteenth century painting[4] shows the Glasgow skyline covered with chimneys. Substantial industrial activity occurred in areas due south of Glasgow, and west along the River Clyde. Other than the Glasgow conurbation, the closest mainland pollution source east of Arran is Ardrossan, ~20 km away, although there could have been a more local contribution from the Ardrossan–Brodick ferry.

3.1. Arran smoke pollution concentrations

Smoke concentrations on Arran are now estimated from the Goatfell PG data. On 10th–11th October 1859 Kelvin measured the PG with his portable electrometer at Goatfell and on the beach, whilst an assistant stayed at Invercloy to watch the house electrometer. Kelvin reports the PG measurements relative to the values measured at the house, "about 350 degrees" deflection of the divided ring electrometer, 270–285 $\mathrm{Vm^{-1}}$ from the calibration in section 1. The house and beach values were usually within a few percent of each other, but the PG at Goatfell was reported to be a factor of 1.13–3.06 greater than the house value over a 3 h period[5] (Thomson, 1872). The Goatfell PG must therefore have been between 305 and 1027 $\mathrm{Vm^{-1}}$. If the fair weather PG is assumed to

[2] The "portable" electrometer still required a dedicated assistant to carry it.

[3] Throughout this paper, PG has been converted into $\mathrm{Vm^{-1}}$ from Kelvin's usual units, elements of the Daniell cell per foot.

[4] *View of Glasgow and the Cathedral* by John A Houston (1812–1884) looking south-west over the city centre, shows ~40 chimneys emitting smoke.

[5] There appears to be a typographical error in the reference: the ratios reported are a factor of 100 too high. Without this assumption the results are unphysical.

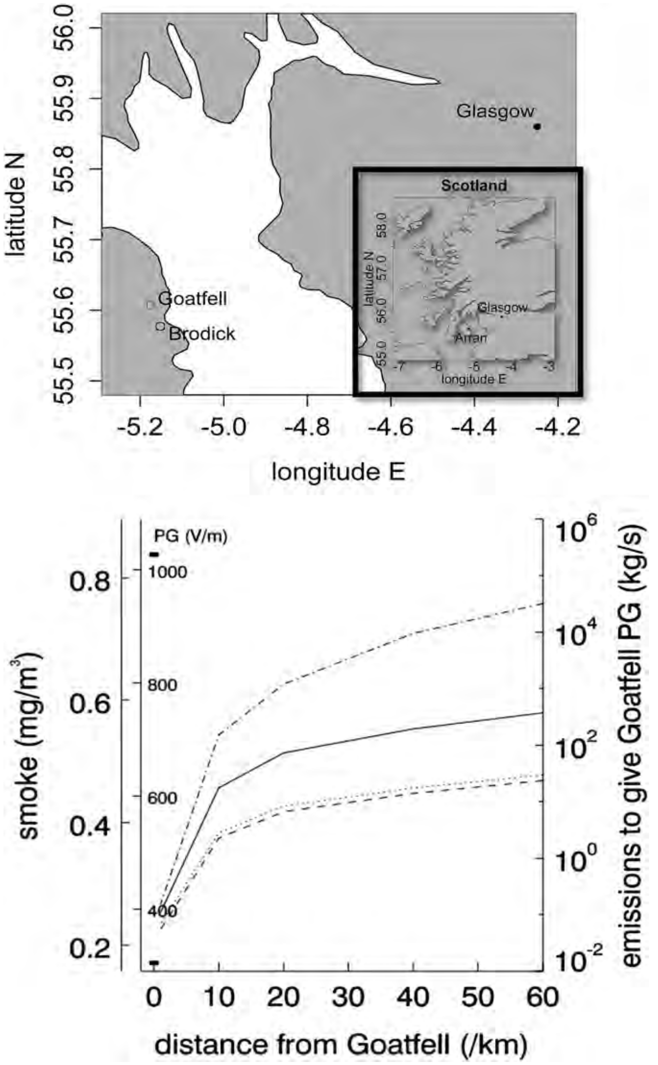

Fig. 1. (*top*) Measurement sites on Arran and (*inset*) overview map of Scotland, showing central Glasgow and Arran. There were two sites at Brodick, Kelvin's house Invergarry, and a beach 55 m away from the house. The approximate location of the Goatfell site is also indicated, described by Kelvin as being between 2 and 2.5 miles from the house, on the path to Goatfell summit (854 m). (*bottom*) PG range at Goatfell on 10th–11th October 1859 (horizontal bars on left) with corresponding smoke concentrations (secondary left axis). Emissions required to give the median smoke concentration at a range of downwind distances from Goatfell, for the conditions during which the observations were made: Pasquill stability category A/wind speed 0.5 ms^{-1} (dot dash line) B/2 ms^{-1} (solid line), D/10 ms^{-1} (dotted line), D/8 ms^{-1} (dashed line).

be 130 Vm^{-1} and its enhancement is entirely from smoke pollution, the Harrison (2006) calibration indicates that the pollution at Goatfell on 10th–11th October 1859 would have been 0.17–0.84 mg m^{-3}, suggesting a typical concentration of ~0.5 mg m^{-3}. (It is not possible to assume the enhanced PG is solely from smoke for the house measurements, due to the possible effects of sea spray. Smoke levels are therefore not calculated for the house data). The pollution levels inferred for Goatfell are comparable to, or greater than London pollution in the same period (Harrison and Aplin, 2002; Brimblecombe, 1987), but could represent the integrated emissions from an entire, highly polluted, region of industrial Western Scotland. A standard Gaussian plume modelling approach (Seinfeld and Pandis, 1997) has been used to estimate the emission rates which would have been required to generate such smoke concentrations on Arran.

3.2. Likely source sites and emission rates

To derive distant smoke concentrations, a Gaussian plume model requires an emission rate, wind speed information, and an atmospheric "stability class" to estimate the dispersion as a function of turbulence (Seinfeld and Pandis, 1997). The detailed qualitative notes taken by Kelvin can be readily used to estimate the simple stability categories first defined by Pasquill (1961), which classified the turbulence from solar radiation, cloud cover and surface wind speed. As the measurements were made during fair weather on an autumnal day, "moderate daytime" conditions can be applied, with the stability class only depending on the wind speed. The PG data was obtained during wind speeds from "calm" and "light easterly" winds, assumed to be ~0.5 and 2 ms^{-1} respectively, corresponding to Pasquill stability classes A and B. The windiest conditions under which the PG was increased was when sea spray was blowing slightly inland, suggesting stability class D and 8-10 ms^{-1} from the Beaufort scale (e.g. McIlveen, 1992). These wind speeds and directions are similar to those reported at Armagh Observatory,[6] 167 km south-south-west of Brodick, for 10th–11th October 1859. Using the four sets of possible dispersion conditions in the Gaussian plume estimates,[7] Table 1 summarises the necessary emission rates to generate the range of possible smoke concentrations observed at Goatfell. These may represent upper limits, since Kelvin was likely to have only been able to obtain consistent atmospheric electricity data during relatively stable conditions that were less effective at pollution dispersal than Table 1 implies. No local meteorological data are available, but the Armagh pressure record indicates that there could have been anticyclonic weather during Kelvin's measurements, which would be consistent with an easterly wind over both Armagh and Arran. More stable conditions could also have trapped the pollution in layers close to the emission height, which would explain the higher PG observed at Goatfell compared to the house. In the absence of any other local meteorological observations for this period, the stability classes in Table 1 have been based on Kelvin's recorded observations.

Fig. 1 (bottom section) also shows the emission rate required to generate the observed smoke concentrations, against downwind distance from Goatfell. Clearly this range of sources in industrial western Scotland could all have contributed to Arran smoke pollution, although central Glasgow remains the most distant likely source, ~60 km away. Other sources seem possible, for example, the major shipbuilding activity on the River Clyde, to the west of Glasgow.

The emission rates needed to generate 0.5 mg m^{-3} smoke at 60 km downwind vary over four orders of magnitude, from >10 tonnes to 1 kg s^{-1}. No contemporary quantitative measurements exist with which to directly constrain these emission rate estimates: the first particulate data for Glasgow was the mass flux of "smuts" (falling oily deposits and soot), recording 820 tons/square mile (mi^2) in 1909 and 326 tons/mi^2 in the early 1920s (Thorsheim, 2006). For comparison, early direct London pollution measurements were ~0.6 mg m^{-3} in the early 1920s, with 353 tons/mi^2 of smuts (Harrison, 2006; Thorsheim, 2006). Assuming a linear scaling between mass concentration and smuts, the smoke pollution concentration in Glasgow in 1909 would exceed 1 mg m^{-3}. Using this concentration for Glasgow with the Gaussian plume model is incompatible with the 0.5 mg m^{-3} measured at Goatfell (Fig. 1). Rather than discount the in situ measurements, which

[6] http://climate.arm.ac.uk accessed December 2011.

[7] http://www.csun.edu/~vchsc006/469/gauss.htm accessed August/September 2011.

Table 1
Kelvin's description of conditions during the increased PG measurements (October 10th–11th 1859) with estimated wind speeds for these conditions. Pasquill stability classes (Pasquill, 1961) have been estimated from the wind speeds, using the assumption of "moderate daytime" conditions. Emissions needed to give the maximum and minimum smoke concentrations from a source 60 km upwind of Goatfell, using a Gaussian plume model, are also shown.

Lord Kelvin's wind description (Thomson, 1860)	Estimated wind speed (ms^{-1})	Pasquill stability class	Source emission rate ($kg\,s^{-1}$) required for 0.17 $mg\,m^{-3}$ at 60 km downwind	Source emission rate ($kg\,s^{-1}$) required for 0.85 $mg\,m^{-3}$ at 60 km downwind
"Calm"	0.5	A	10,800	54,000
"Light easterly"	2	B	126	630
"Fresh temporary breeze of east wind, blowing up a little spray"	8–10	D	8–10	40–50

appear reliable, this difference can be resolved if there are additional sources between Glasgow and Arran.

Hence it seems more likely that the major sources were nearer to Arran than Glasgow, and originated from River Clyde industry, or were perhaps directly south of Glasgow, ~40 km from Arran. A source 20–40 km from Goatfell would require integrated emissions of $\sim 10–10^4\ kg\,s^{-1}$ to give smoke concentrations compatible with the Goatfell PG. Kelvin (Thomson, 1859) reported seeing haze to the east during many of the high PG measurements, suggesting that the pollution was principally generated by fine aerosol, which would have remained aloft for longer than larger smoke particles from a distant source. This is consistent with the Harrison (2006) calibration between PG and aerosol mass concentration, which included a contribution from smaller particles.

4. Discussion

Using the atmospheric electricity proxy method as discussed, the estimated local smoke concentration at Goatfell on Arran lies between 0.17 and 0.84 $mg\,m^{-3}$. Quantitative context is that it exceeds nineteenth-century smoke concentrations retrieved for Paris and London, and also those for eighteenth-century London (Harrison and Aplin, 2002, 2003; Harrison, 2009). In terms of the emission characteristics, Arran was downwind of a polluted region rather than just a single urban source. This is supported by the early measurements of Glasgow soot deposits, which indicate that emissions were insufficient to generate 0.5 $mg\,m^{-3}$ at 60 km downwind.

Further evidence for this emissions scenario is that one early 20th century London gasworks consumed 2200 tonnes of coal daily, corresponding to an emission rate of 200 $kg\,s^{-1}$ (Thorsheim, 2002). Such a single source at ~20–40 km from Goatfell could generate smoke concentrations comparable with those retrieved under light easterly winds (stability class B). Considering a smaller-scale possibility, Ge et al. (2001) report that a contemporary Chinese coal-burning boiler emits PM10 at 0.01 $kg\,s^{-1}$, so the equivalent of between 10^3 and 10^7 modern boilers would be needed to generate the smoke levels derived. Victorian coal burners are likely to have been less efficient, and emitted smoke as well as smaller PM10 particles, suggesting that the estimate above is conservative. Emissions of up to $\sim 10^4\ kg\,s^{-1}$ are therefore not unreasonable, assuming multiple industrial smoke sources in western Scotland.

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