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Multi-station synthesis of early twentieth century surface atmospheric electricity measurements for upper tropospheric properties

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Abstract. The vertical columnar current density in the global atmospheric electrical circuit depends on the local columnar resistance. A simple model for the columnar resistance is suggested, which separates the local boundary layer component from the upper troposphere cosmic ray component, and calculates the boundary layer component from a surface measurement of air conductivity. This theory is shown to provide reasonable agreement with observations. One application of the simple columnar model theory is to provide a basis for the synthesis of surface atmospheric electrical measurements made simultaneously at several European sites. Assuming the ionospheric potential to be common above all the sites, the theoretical air-earth current density present in the absence of a boundary layer columnar resistance can be found by extrapolation. This is denoted the free troposphere limit air-earth current density, J_0. Using early surface data from 1909 when no ionospheric potential data are available for corroboration, J_0 is found to be $\sim$6 pA m^{-2}, although this is subject to uncertainties in the data and limitations in the theory. Later (1966–1971) European balloon and surface data give J_0=2.4 pA m^{-2}.

1 Introduction

In the global atmospheric electrical circuit, a fair-weather current flows vertically between the ionosphere and the surface, which is related to the ionosphere-surface potential difference and the resistance of the atmospheric column. This charge transfer results because atmospheric air is weakly electrically conductive, as a result of radioactive ion production from Radon isotopes in continental surface air and cosmic ray ionisation elsewhere (Harrison and Carslaw, 2003). Long-term global circuit changes (Harrison, 2002; Märcz and Harrison, 2005) have been suggested to result from the twentieth century reduction in galactic cosmic ray ion production from increased solar activity (Lockwood et al., 1999; Carslaw et al., 2002), but the analysis of surface data from a single site is complicated as smoke and aerosol concentrations exert a local influence on surface atmospheric electrical measurements (Williams, 2003). Solar activity increased during the twentieth century, and a greater change occurred in approximately the first half of the century than the second half of the century (Lockwood, 2001). Most atmospheric electricity measurements in the first half of the twentieth century were made at the surface (Harrison, 2004), but a 1909 to 1959 reduction in lower atmosphere ion production is apparent in early European balloon-carried atmospheric electricity measurements (Harrison and Bennett, 2007).

The potential of the ionosphere with respect to the surface is a measurable parameter in the global atmospheric electrical circuit (Fig. 1). Direct measurements of the ionospheric potential are available in the second half of the twentieth century (e.g. Ungethüm, 1966; Imyanitov and Chubarina, 1967; Mülheisen, 1971; Markson, 1985). Although instrumented balloon ascents began in the late nineteenth century (Israël, 1970, 1973), these early ascents did not reach sufficient altitudes to permit the ionospheric potential to be directly calculated (Harrison and Bennett, 2007). Measurements of atmospheric electrical properties above the surface are, however, important in assessing global geophysical changes in atmospheric electricity, as regions of the troposphere above the continental boundary layer are relatively little affected by surface aerosol changes. To obtain quantitative data in the period before direct and routine balloon measurements, a new approach is developed here, in which simultaneous measurements from several surface observation sites are combined to reduce local surface effects.

A discussion of data analysis using multiple site measurements in the first half of the twentieth century was given by Israël (1973), based on the results of Hogg (1950). Hogg

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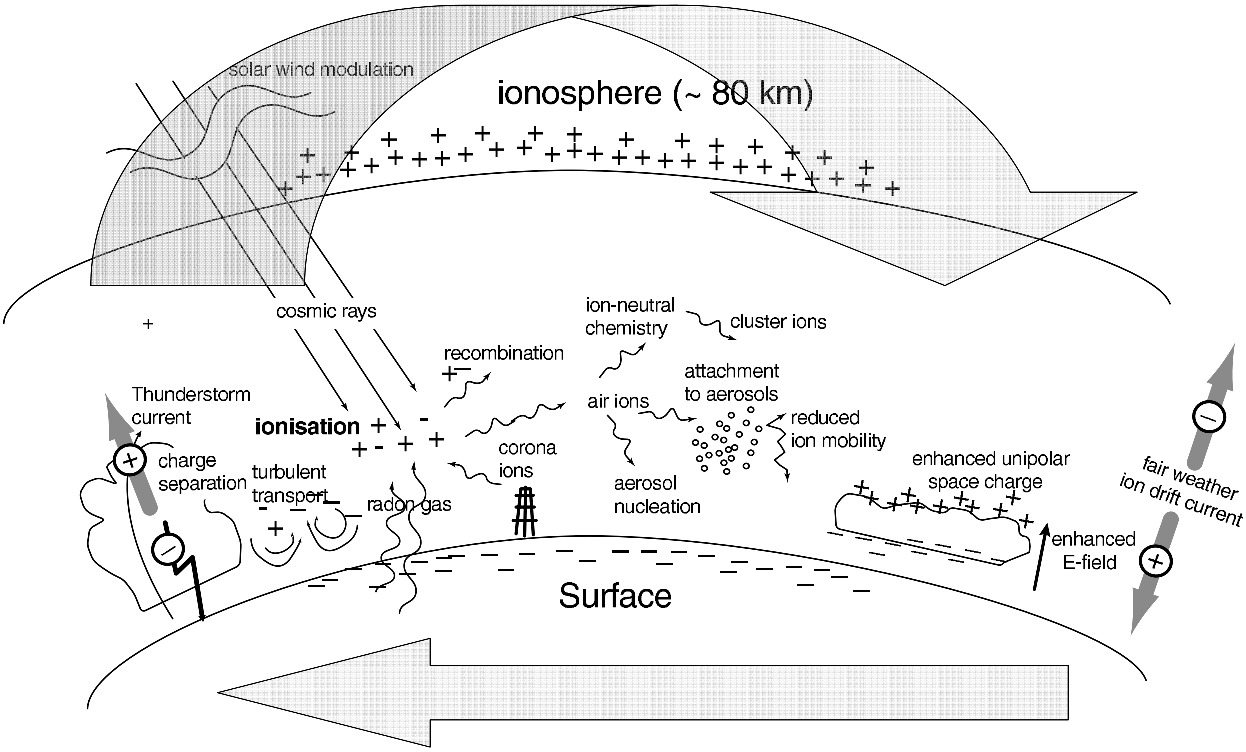

Fig. 1. Charge separation processes in the atmosphere (adapted from Harrison and Carslaw, 2003). Large arrows illustrate current flowing in the global circuit, in the conducting ionosphere and planetary surface. The fair weather current between ionosphere and surface results from the small finite conductivity of atmospheric air, principally due to cosmic ray ionisation.

found that, if the mean air-earth current density was plotted against the mean surface air conductivity, the measurements from different global sites clustered around a line. The non-linear relationship showed that the air-earth current density J_z increased with the surface air conductivity σ_s. For large values of σ_s (i.e. increasingly clean air), J_z extrapolated to $J_z>5\,\mathrm{pA\,m^{-2}}$, although an exact asymptotic value was not clearly identified. Using a vertical profile of the air conductivity, Hogg (1950) deduced the value for the ionospheric potential V_I to be 340 kV.

2 Theory for columnar properties

The vertical columnar resistance R_c determines the current density J_z flowing between the ionosphere and the surface (Israël, 1970), and typically varies between 130 and 300 $\mathrm{P\Omega\,m^2}$ (Roble and Tzur, 1986). In principle, R_c is defined by integrating the resistances of all atmospheric layers between the surface and ionospheric equipotential layer. In practice, R_c can be found through solving the ion-aerosol balance equation (Harrison and Carslaw, 2003) for the air conductivity as a function of altitude, and then integrating the conductivity profile. This approach requires local aerosol and ion production rate profiles. The effect of aerosol on the conductivity profile is most substantial in the continental boundary layer (BL), but cosmic rays have an increasingly dominant effect above the boundary layer, in the free troposphere (FT) (Callahan et al., 1951). Accordingly, the total columnar resistance can be represented by a free troposphere component R_{FT} and a boundary layer component R_{BL}, as

$$R_c = R_{BL} + R_{FT}. \tag{1}$$

The R_{BL} term is variable, and depends on surface aerosol concentrations and mixing of the Radon isotopes. The R_{FT} term is relatively constant, with variability from cosmic ion production changes with solar activity and volcanic aerosol injection into the stratosphere(Fig. 2a). Variation of cosmic ray ion production with geomagnetic latitude will also cause R_{FT} to vary between sites located at substantially different latitudes.

A simple approximation is used here to represent R_{BL}. Analysing R_c variations in 1966–1971 at Kew (Harrison, 2005), it was found that R_{BL} was closely linked to the measured surface air conductivity. This can be understood in terms of a shallow layer of low conductivity air causing the lower atmosphere resistance. In such circumstances, R_{BL} would be inversely proportional to the conductivity of the air in this layer (Fig. 2b). The exact relationship depends on the form of the conductivity profile chosen: it could be repre-

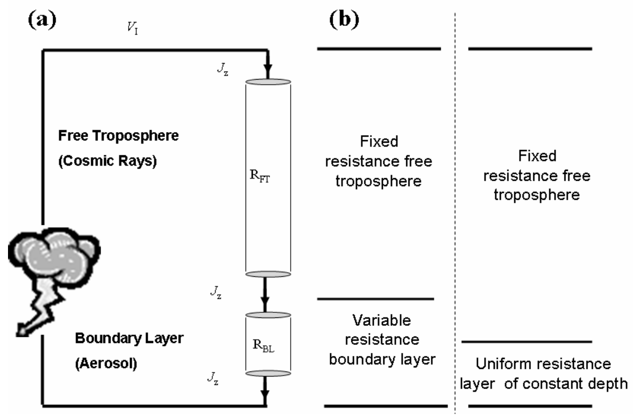

Fig. 2. **(a)** Columnar resistance in the global circuit. The columnar resistance R_c determines the local global circuit current density J_z. R_c consists of a boundary layer component R_{BL}(from aerosol and radon isotopes) and a free troposphere component R_{FT} (from cosmic rays). **(b)** R_{BL} can be represented by a resistive layer of variable height, or approximated by a shallow fixed depth layer of variable resistance.

sented as a variable thickness layer with a varying conductivity, or an equivalent fixed height layer of constant conductivity. Using the surface air conductivity σ_s to determine the constant resistance layer near the surface, (1) can be written as

$$R_c = \frac{k}{\sigma_s} + R_{FT}, \tag{2}$$

where k is a proportionality constant related to the conductivity profile in the polluted layer, but can be equivalently understood physically as representing the height of a constant conductivity layer. Calculation of the terms in Eq. (2) is now considered further.

The air-earth current density J_z is related to the ionospheric potential V_I and columnar resistance R_c by

$$J_z = \frac{V_I}{R_c}, \tag{3}$$

which permits Eq. (2) to be written as

$$\frac{V_I}{J_z} = \frac{k}{\sigma_s} + R_{FT}. \tag{4}$$

Equation (4) links surface (σ_s) and balloon sounded quantities (V_I), through the column quantities of the air-earth current density J_z and the free troposphere resistance R_{FT}. Making the low turbulence approximation (Tammet et al., 1996), Ohm's Law can be used to link surface measurements of PG E_s and σ_s

$$J_z = \sigma_s E_s, \tag{5}$$

giving a further form for Eq. (4) as

$$\frac{V_I}{E_s} = k + R_{FT}\sigma_s. \tag{6}$$

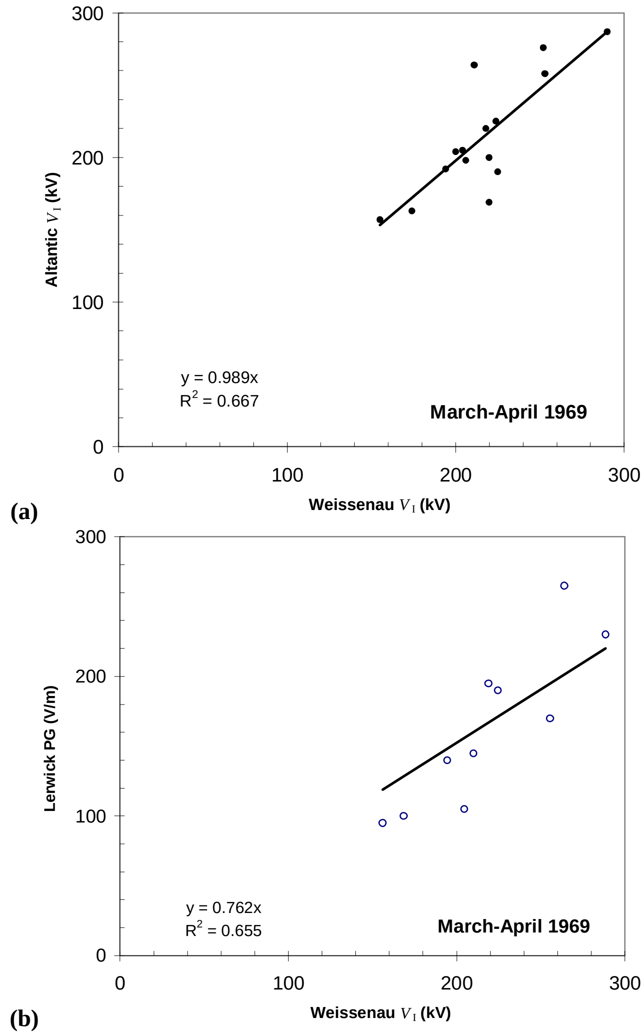

Fig. 3. Comparison of Weissenau ionospheric potential measurements with simultaneous measurements, when available, of **(a)** ionospheric potential determined over the north Atlantic using balloon soundings from the research ship *Meteor* (17 March to 2 April 1969), **(b)** the surface potential gradient (PG), measured at Lerwick in fair weather or non-hydrometeor conditions (17 March to 2 April 1969).

Data to test the validity of the approximations in deriving Eq. (6) are rare, however the ionospheric potential measurements by R.Mülheisen at Weissenau, Germany (e.g. Mülheisen, 1977), and the frequent Wilson instrument air-earth current density and PG measurements made at Kew by the UK Met Office (Harrison and Ingram, 2005) were occasionally coincident and provide suitable data for analysis. Some of the daily measurements of J_z and σ_s at Kew coincided with V_I soundings made from Weissenau in 1966–1971 (Harrison, 2005).

A necessary assumption for this comparison is that that the V_I soundings made from Weissenau also represented the

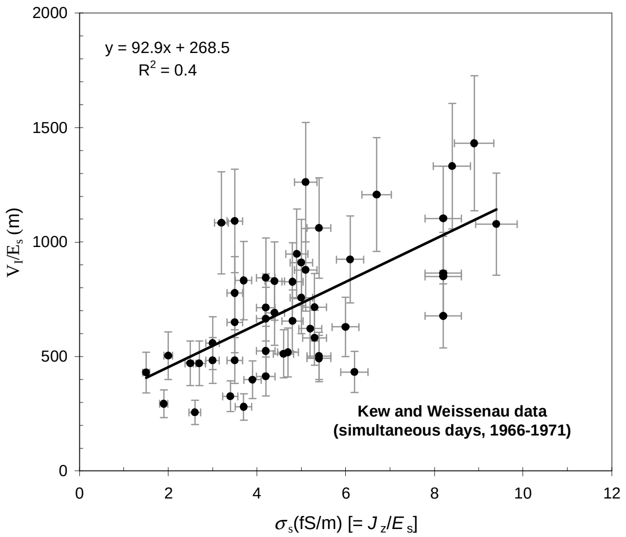

Fig. 4. Daily measurements of ionospheric potential V_I (over Weissenau) and surface measurements from Kew on the same days of potential gradient E_s and air conductivity σ_s, with σ_s plotted against V_I/E_s. A 20% worst-case uncertainty has been assumed for V_I, and 5% for E_s and σ_s (data from Harrison, 2005).

V_I above Kew, i.e. that a common equipotential surface existed above both sites, as expected from the global circuit model. Confirmation of this spatial equipotential assumption requires, at least, corroboration with simultaneous measurements in the same region. Surface measurements were made throughout this period at Lerwick, Shetland, and further V_I soundings are available made in the western Atlantic. The V_I measurements were led by Mülheisen, using the *Meteor* research ship. Many of the soundings made from the *Meteor* were simultaneous with soundings made from Weissenau (Mülheisen, 1971). Figure 3a shows a comparison between V_I soundings made at Weissenau and those from the *Meteor*, during the observation period in March and April 1969, from data tabulated by Buduko (1971). There is close agreement in the V_I values obtained at the two sites. Figure 3b shows a comparison between Lerwick PG measurements and the Weissenau V_I soundings, for PG measurements simultaneous with the soundings when the conditions at Lerwick were either classified as fair weather or no hydrometeors were recorded. There is a linear relationship between the Lerwick PG and the Weissenau V_I, which implies that the surface PG at Lerwick was modulated by the ionospheric potential above. This agreement between the measurements at Lerwick, *Meteor* and Weissenau, which geographically bound a triangle including Kew Observatory in the southern UK, provides the basis for considering the Weissenau V_I soundings as representative of the ionospheric potential above Kew.

Figure 4 shows the comparison between the surface and balloon measurements, plotted in terms of the model represented by Eq. (6). The Kew surface measurements using the Wilson technique determined E_s and J_z independently, as E_s was obtained by measuring the induced potential on the sensing plate, and J_z from the rate of change of E_s. (The local air conductivity was calculated assuming Ohms Law' i.e. $\sigma_s = J_z/E_s$). Figure 4 can therefore equivalently be regarded as a plot of (V_I/E_s) against (J_s/E_s), in which all three quantities are determined separately. The model provides a significant fit to the experimental data (49 points, r=0.61), showing that Eq. (6) does provide a representation of the physical processes concerned, under the assumptions made. Figure 4 also allows determination of R_{FT}=(92.9±18) PΩ m^2 and k=(268±92) m. This indicates that R_{BL} can be represented by an equivalent constant conductivity layer of fixed depth 268 m, with the layer containing air of conductivity equal to the measured surface conductivity. The mean values of air-earth current density at Kew for the same period (1966–1971) was J_z=(1.58±0.04) pA m^{-2} and the mean ionospheric potential V_I=(217±4) kV, giving a columnar resistance at that site of R_c=137 PΩ m^2 calculated from Eq. (3). Applying Eq. (1) allows R_{BL} to be found from the values of R_c and R_{FT}.

A theoretical limiting case can be considered, in which only the upper atmosphere term contributes resistance and there is no contribution from the lower atmosphere, i.e. when R_{BL}=0. In such conditions, the current density flowing would be increased, as $R_c = R_{FT}$. The current density in these circumstances is denoted the *free troposphere limit air-earth current density* J_0.J_0 provides a measure of upper properties of the columnar independently of the surface properties. For the 1966–1971 values analysed, J_0=2.4 p Am^{-2}.

3 Extension to historical atmospheric electrical data

3.1 Formulation

Many early surface atmospheric electricity records exist of Potential Gradient measurements. Some European sites also measured the air-earth current density J_z and surface ion properties (number concentrations and mobilities) or the air conductivity σ_s. A summary of data sources is given in Harrison (2004). Whilst these could in principle provide useful data for Eq. (6), there are, as mentioned earlier, no direct measurements of V_I from the first half of the twentieth century. This precludes the use of Eq. (6) at a single site. However as V_I is a global equipotential, the surface atmospheric electrical measurements made simultaneously at different sites will all have experienced the same V_I above them (Fig. 5). A set of simultaneous measurements from several sites consequently contains information about the average global circuit properties common to them all, and the ratios of their local columnar resistances (Harrison, 2007).

If a plot of J_z against σ_s were made for a set of simultaneous measurements from different sites (e.g. Hogg, 1950), J_z

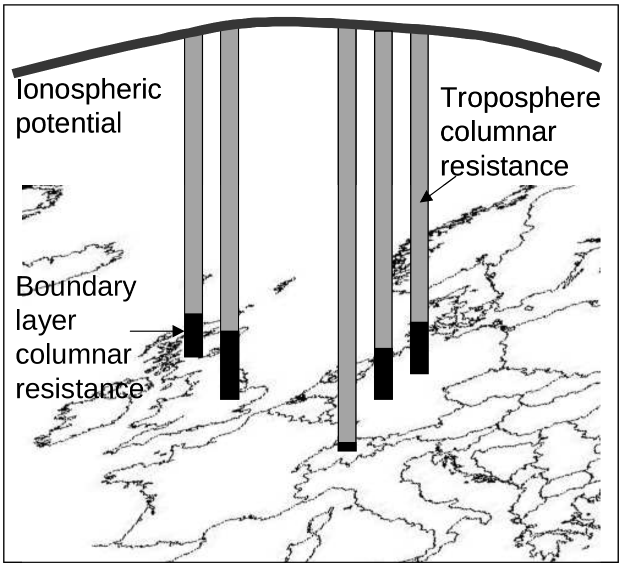

Fig. 5. Schematic of the effect of global circuit changes on simultaneous measurements of the air-earth current density at different European sites. The ionospheric potential has a constant value above all the sites. The columnar resistance consists of a free troposphere component (shaded dark gray), and a boundary layer part component (shaded black).

would increase non-linearly with σ_s, and approach an asymptotic value. Physically, this asymptotic value arises when the (local) lower atmosphere resistance term (R_{BL}) becomes negligible compared with the (global) upper atmosphere resistance (R_{FT}). In the limit as $\sigma_s \rightarrow \infty$, the asymptotic value of current density becomes the free troposphere current density J_0. This limit provides a method for determining J_0 from surface measurements, by using the linear theory in the limit as $(1/\sigma_s) \rightarrow 0$.

Equation (4) can be rearranged to give

$$\frac{1}{J_z} = \left(\frac{k}{V_I}\right)\frac{1}{\sigma_s} + \frac{R_{FT}}{V_I}. \tag{7}$$

This separates the boundary layer effects (first term on RHS) from the free troposphere effects (second term on RHS), which both determine the air-earth current density J_z at a specific location. This form of the equation is particularly useful as the second RHS term is independent of the boundary layer properties k and σ_s. If the boundary layer is considered to become highly electrically conductive, i.e. allowing $(1/\sigma_s) \rightarrow 0$, only the free troposphere term remains. In this theoretical limit, the corresponding value of J_z would be that corresponding to R_{BL}=0, which is the limiting condition J_z=J_0. Equation (7) therefore provides a basis for the calculation of J_0 from surface measurements alone, if simultaneous, multiple site, values of J_z and σ_s are available.

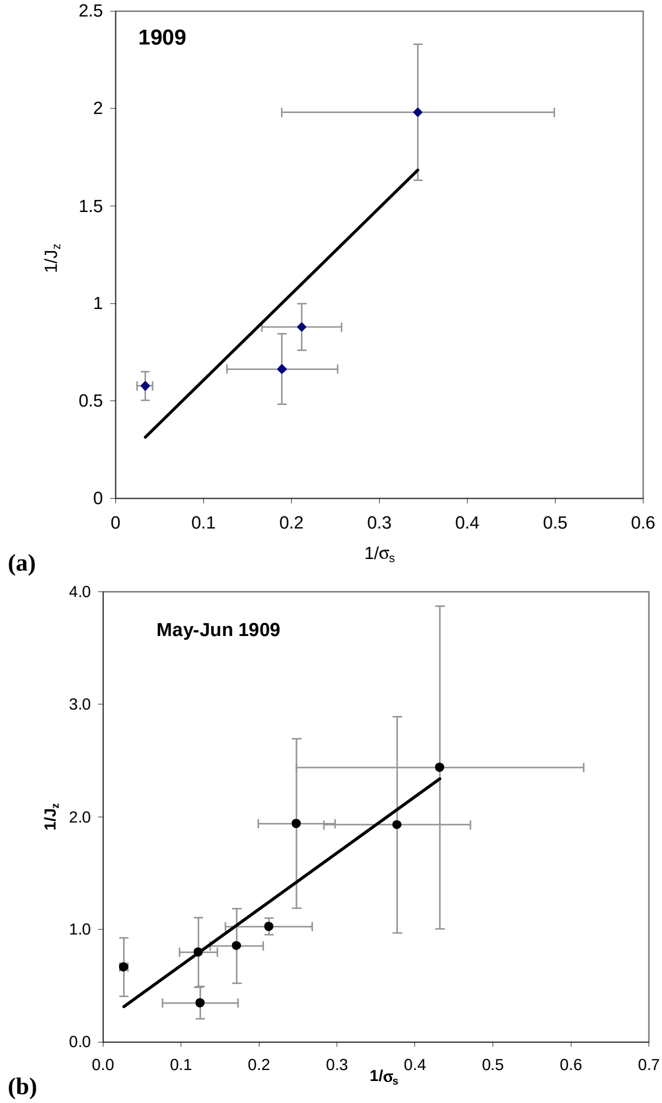

Fig. 6. Measured air-earth current J_z and σ_s plotted according to Eq. (7) for **(a)** Davos, Munich, Kew and Potsdam in 1909 and **(b)** for Davos, Munich, Kew, Potsdam and Edinburgh in May–June 1909. (Error bars are from one standard deviation. For Davos, Munich and Potsdam in (b), the fractional standard deviation was assumed to be the same as that for Kew.)

3.2 Test with 1909 data

Simultaneous data sets are relatively rare in atmospheric electricity, but such measurements were more common in the first part of the twentieth century. Measurements from the early twentieth century, from Europe in 1909, have been used to test Eq. (7). These are:

1. Annual measurements of σ_s and J_z, given as monthly values for Munich, Davos, Kew and Potsdam in 1909 (Dobson, 1914)

Table 1. Annual averages for surface air conductivity and air-earth current density for Potsdam, Kew, Munich and Davos in 1909.

Site	Total conductivity ($fS\,m^{-1}$)		Air-earth current density ($pA\,m^{-2}$)	
	Annual mean	standard deviation	Annual mean	standard deviation
Potsdam	4.72	1.0	1.14	0.2
Kew	2.91	1.3	0.5	0.1
Munich	5.28	1.8	1.51	0.4
Davos	29.88	7.9	1.73	0.2

Table 2. Averages for surface air conductivity and air-earth current density Davos, Munich, Kew, Potsdam and Edinburgh, for May–June 1909.

Site	Total conductivity $fS\,m^{-1}$	Air-earth current density $pA\,m^{-2}$
Edinburgh Obs	2.31	0.41
Edinburgh Obs	2.65	0.52
Waverley Park	4.70	0.97
Blackford Hills	8.02	2.87
Kew	4.03	0.52
Munich	8.17	1.26
Davos	37.30	1.5
Potsdam	5.83	1.17

2. May-June values for 1909 σ_s and I_z for Munich, Davos, Kew and Potsdam (Dobson, 1914) and Edinburgh (Carse and MacOwan, 1910).

These measurements sites all have, in common, air within a continental boundary layer, but a range of different air pollution conditions. Tables 1 and 2 give values of σ_s and J_z from these sources.

Figure 6 plots the data values as $(1/J_z)$ against $(1/\sigma_s)$, for (a) the annual values and (b) the May–June values, with least-squares straight lines added. In Fig. 6a, the use of an annual value compensates to some extent for different seasonal cycles between the different sites, however there are only four values. In Fig. 6b, extra points are available, but the validation of Eq. (6) may be less appropriate as only a short period of data (2 months) is available, and seasonal effects will not be removed in the same way. It is clear from both plots, however, that extrapolation to $(1/\sigma_s)$=0 provides a finite positive value of J_0. Using the annual values (Fig. 6a), the most probable J_0=6.0 $pA\,m^{-2}$, with a (1 standard error) lower limit of 1.7 $pA\,m^{-2}$. For summer values (Fig. 6b), the linear fit gives J_0=5.6 $pA\,m^{-2}$ (lower limit of 1.3 $pA\,m^{-2}$).

4 Conclusions

A multi-station synthesis approach seems particularly useful for determining global circuit properties in the period before balloon or aircraft ascents reached sufficient altitudes to obtain direct measurements of the ionospheric potential, i.e. for the first half of the twentieth century, when many sets of surface measurements are available.

The use of a simple approximation to the boundary layer columnar resistance provides a basis for a multi-station synthesis of atmospheric electricity measurements, which permits estimation of electrical properties above the boundary layer without using data requiring balloon ascents. The method assumes that the shape and variations in the conductivity profile at each site can be represented in a similar way on average, although the absolute surface layer columnar resistances are allowed to be different. For the sites examined, the variability in the data is likely to dominate over the uniform conductivity profile assumption. At many sites, such as the Marsta Observatory in Sweden (Israelsson and Tammet, 2001), the winter boundary layer shows so little variability that surface measurements in the PG exhibit the global circuit (Carnegie) variation in the diurnal data. The regularity in this behaviour across many years indicates that a uniform conductivity profile assumption is reasonable.

The free tropospheric current J_0 derived for 1909 in Europe is poorly constrained because of the variability in the available data and the limitations of the linear theory applied, but is estimated to be greater than 1.7 $pA\,m^{-2}$, with a probable value of 6 $pA\,m^{-2}$. This compares with the direct determination of J_0=2.4 $pA\,m^{-2}$ obtained in 1966–1971, for a similar region. This suggests a reduction in the global circuit current density, qualitatively consistent with the reduction in cosmic ray ion production determined in other studies for the first half of the twentieth century.

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