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Solar modulation in surface atmospheric electricity

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ABSTRACT

The solar wind modulates the flux of galactic cosmic rays impinging on Earth inversely with solar activity. Cosmic ray ionisation is the major source of air's electrical conductivity over the oceans and well above the continents. Differential solar modulation of the cosmic ray energy spectrum modifies the cosmic ray ionisation at different latitudes, varying the total atmospheric columnar conductance. This redistributes current flow in the global atmospheric electrical circuit, including the local vertical current density and the related surface potential gradient. Surface vertical current density and potential gradient measurements made independently at Lerwick Observatory, Shetland, from 1978 to 1985 are compared with modelled changes in cosmic ray ionisation arising from solar activity changes. Both the lower troposphere atmospheric electricity quantities are significantly increased at cosmic ray maximum (solar minimum), with a proportional change greater than that of the cosmic ray change.

1. Introduction

Surface measurements of atmospheric electricity have long been thought to show evidence of solar modulation. Early statistical comparisons of the surface potential gradient and sunspot activity associated with terrestrial magnetism supported this view (Chree, 1906; Bauer, 1925), but physical explanations for correlations were not readily apparent. Surface atmospheric electricity measurements made during the first half of the twentieth century appeared to vary in phase with the 11-year (Schwabe) cycle of solar activity (Israël, 1973), but later work, which identified the importance of cosmic rays, showed an anti-phase response to solar activity. For example, cosmic rays showed a positive correlation with the ionospheric potential during the late 1960s and early 1970s (Mülheisen, 1977; Markson and Muir, 1980; Markson, 1981). Establishing whether the sign and existence of solar effects in atmospheric electricity has varied with time requires study of measurements from a variety of periods and sites.

The global atmospheric electrical circuit (Rycroft et al., 2000) drives current from disturbed weather regions to fair weather regions, through the positively electrified ionosphere. In fair weather regions this causes a small current to flow continuously between the ionosphere and the surface. Variations in the total conductivity of an atmospheric column change the local vertical current density flowing in fair weather regions, and the associated potential gradient at the surface. As galactic cosmic rays provide the principal source of ionisation causing the conductivity of atmospheric air, solar modulation of cosmic ray ionisation physically links solar activity with the lower atmosphere through atmospheric electricity. The vertical current flow is known to be sustained through regions of water droplets (Bennett and Harrison, 2009), and, specifically, cloudy conditions (Nicoll and Harrison, 2009). If clouds respond to the current flow, modulation of the fair weather vertical current density would provide a potential climate influence, because of the sensitivity of the atmospheric energy balance to cloud properties. Cloud edge charging effects on the microphysics of stratiform clouds from the vertical current density have been suggested (Zhou and Tinsley, 2007; Harrison and Ambaum, 2008).

Atmospheric electricity measurements are rare compared with meteorological measurements, which hampers studies of solar influences. The most abundant measurements made are those of the surface potential gradient (PG), with the vertical conduction current density (J_c) measured at only a few sites globally. In general J_c measurements are preferable as they show much smaller local pollution effects than PG (Märcz and Harrison, 2005), but, as studies into solar effects require long period ($\sim$several years to decades) surface atmospheric electricity data, insufficient data duration presents a practical difficulty in separating solar-induced atmospheric electricity changes from other effects. Analysis methods include comparison of transient changes in atmospheric electricity coincident with solar flares (Cobb, 1967) or Forbush cosmic ray decreases (Märcz, 1997), and identification of periodicities characteristic of cosmic rays (e.g. at 1.68 years during the 1980s) in long term PG data (Harrison and Märcz, 2007). Using J_c data obtained from 1966 to 1977 by Prof. D. Olson over northern Minnesota, Markson and Muir (1980)

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reported a 30% solar cycle variation in J_c, in phase with the galactic cosmic ray variation. The difference in phase of response to the solar cycle in Olson's measurements from measurements in the first half of the twentieth century has been attributed to changes in stratospheric aerosol loading following volcanic eruptions (Tinsley, 2005). A further possible explanation is that the earlier measurements were incompletely compensated for surface air conductivity variations.

To investigate the phase and magnitude responses to solar changes in lower troposphere atmospheric electricity, a later (1978–1985) series of northern latitude measurements made by the UK Met Office at their Lerwick Observatory (Shetland Islands) is studied here. This island site has little local pollution and frequent rainfall, yielding intermittent periods of fair weather atmospheric electricity conditions. The Lerwick surface J_c and PG data show properties characteristic of clean air, such as correlated variations of the independently observed J_c and PG (Harrison and Nicoll, 2008). Good agreement between simultaneous European and Atlantic measurements of the global circuit's ionospheric potential and the Lerwick PG has also been observed (Harrison and Bennett, 2007; Rycroft et al., 2008). Additionally, the PG measured at Lerwick during September 1928 showed similarities with Atlantic PG measurements made on cruise VII of the geophysical research ship *Carnegie*, (Harrison, 2004a). The late Lerwick measurements are considered here in terms of solar changes, using a model to calculate the expected solar-induced column ionisation changes above the measurement site (Usoskin and Kovaltsov, 2006).

2. Data analysis

2.1. Lerwick atmospheric electricity data

Lerwick Observatory remains an operational geophysical and meteorological site, which, from 1926 to 1985, made routine hourly PG measurements. From 1978 to 1985, J_c measurements were also made. The PG was measured using a radioactive probe, and J_c was measured with a horizontal collecting plate, as described by Harrison and Nicoll (2008). Following their investigation and in common with the Met Office conventions in atmospheric electricity, the 15 UT measurements are used here for further analysis. Fig. 1 shows time series of the 15 UT PG and J_c from Lerwick in fair weather, throughout the available J_c measurements. Because of the site's climatology, fair weather periods only occur intermittently and the dataset is sparse with appreciable variability. Robust statistical methods employing threshold tests on median values are therefore used for the analysis. A preliminary aspect is that some seasonality is apparent in the data. The seasonality has been removed by calculating a daily mean value for each day of the year using the available values across the seven years, and fitting a slowly varying (90-day) moving average to the daily mean values found. This smoothed annual cycle was then subtracted from the measured daily values.

From inspection of Fig. 1 no clear 11-year solar cycle variation is seen, which indicates local variations at the site such as those associated with changes in weather conditions, variations in the application of "fair weather" criteria to the data (or limitations in the criteria), or indeed instrument uncertainties. Calculation of the expected local effects from solar-induced changes in cosmic ray ionisation is used for further investigation of the data.

2.2. Columnar resistance variations at Lerwick

Cosmic ray variations arising from solar activity modify the local volumetric ion production rate q. In clean air containing bipolar ions with mean mobility μ, the total air conductivity σ is given by

$$\sigma = 2\mu e\sqrt{\frac{q}{\alpha}} \quad (1)$$

where α is the ion–ion recombination coefficient and e the elementary charge. Analysis of atmospheric electricity changes at Lerwick in the years following nuclear weapon radioactivity deposition showed that the square root dependency of ionisation rate was an appropriate assumption for the site (Pierce, 1972), which illustrates the negligible aerosol concentration present. The conductivity can be integrated with height to determine the total conductance or, more usually, the total resistance. For a unit area column, the columnar resistance R_c is found from

$$R_c = \int_0^{z_I} \frac{dh}{\sigma(h)}, \quad (2)$$

where $\sigma(h)$ represents the total air conductivity variation with height h and z_I is the effective ionospheric height. R_c varies with latitude and with aerosol concentration (Roble and Tzur, 1986). For the polluted site at Kew, London, experimentally derived R_c measurements vary from 64 to 310 PΩ m^2 (Harrison, 2005; Rycroft et al., 2008), from which Harrison and Nicoll (2008) estimated R_c for Lerwick as 70 PΩ m^2, using a short period of overlapping data.

For Eqs. (1) and (2) to be used to calculate R_c, the cosmic ray induced ionisation (CRII) q is required. The CRII can be computed using a numerical model (Usoskin and Kovaltsov, 2006), which considers in detail the nuclear-electromagnetic-muon cascade initiated by energetic cosmic ray particles in the atmosphere. Temporal variations of the cosmic ray spectrum are accounted for

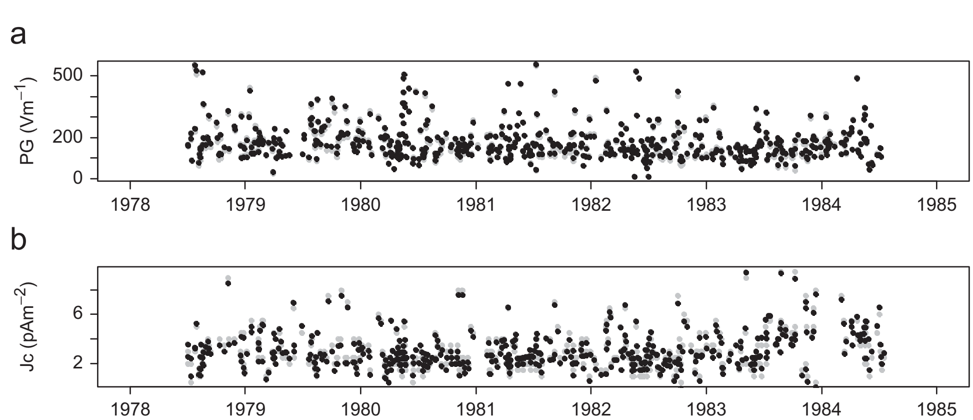

Fig. 1. Daily (15 UT) fair weather atmospheric electricity measurements at Lerwick. (a) Potential Gradient (PG) and (b) conduction current density (J_c). For both plots grey points show the raw data and black points the seasonally corrected values, adjusted by the median of the raw data values.