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Twentieth century secular decrease in the atmospheric potential gradient

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[1] Current flowing in the global atmospheric electrical circuit (AEC) substantially decreased during the twentieth century. Fair-weather potential gradient (PG) observations in Scotland and Shetland show a previously unreported annual decline from 1920 to 1980, when the measurements ceased. A 25% reduction in PG occurred in Scotland 1920–50, with the maximum decline during the winter months. This is quantitatively explained by a decrease in cosmic rays (CR) increasing the thunderstorm-electrosphere coupling resistance, reducing the ionospheric potential V_I. Independent measurements of V_I also suggest a reduction of 27% from 1920–50. The secular decrease will influence fair weather atmospheric electrical parameters, including ion concentrations and aerosol electrification. Between 1920–50, the PG showed a negative correlation with global temperature, despite the positive correlation found recently between surface temperature and V_I. The 1980s stabilisation in V_I may arise from compensation of the continuing CR-induced decline by increases in global temperature and convective electrification. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 2104 Interplanetary Physics: Cosmic rays; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 1650 Global Change: Solar variability

1. Introduction

[2] Current in the atmospheric electrical circuit (AEC) arises from charge-separation in thunderstorms [*MacGorman and Rust*, 1998], causing a vertical potential gradient (PG) in non-thunderstorm (fair weather) zones. The lower conducting layer of the ionosphere, the electrosphere, establishes a global equipotential region, Figure 1. The surface PG in fair weather conditions represents a fraction of the ionospheric potential V_I, and is a measure of the electrical activity of global thunderstorms. In fair weather with no local effects, the diurnal cycles in surface PG and ionospheric potential V_I are similar, resulting from the diurnal cycle in global thunderstorm activity [*Whipple*, 1929]. The diurnal variation was identified in oceanic PG measurements during voyages of the research vessel *Carnegie* in the 1920s: it is a characteristic global signature in atmospheric electrical measurements. Kelvin established surface PG measurements in 1861 at Kew Observatory, London [*Everett*, 1868], and permanent observatories were opened by the UK Meteorological Office at Eskdalemuir, Scotland (55°19′N, 3°12′W) in 1908 and at Lerwick, Shetland (60°8′N, 1°11′W) in 1926. The latter two observatories were remote from sources of pollution and regularly showed the *Carnegie* variation, with rigorous criteria consistently applied to identify the fair weather periods [*Harrison*, 2002]. Hourly measurements of PG ceased at Eskdalemuir and Lerwick in 1981 and 1983 respectively.

2. Prolonged Decrease in Potential Gradient

[3] A remarkable feature of both observatories' measurements [*Dobson*, 1914; *HMSO*, 1912; *Watson*, 1928; *HMSO*, 1965; *UKMO*, 1983] is the previously unreported and prolonged downward trend in the PG from 1920 to 1980, although the 1951–70 data was affected by nuclear weapons testing [*Pierce*, 1972]. Removing the 1951–70 data, the two observatories' annual fair weather PG averages 1927–1981 have a correlation coefficient $r = 0.48$, with a probability P of chance correlation $<2 \times 10^{-5}$. This suggests a common origin to the decline. A downward trend at Lerwick is particularly surprising, as wind directions from northern Europe frequently [*Hamilton*, 1965] increased the Lerwick PG. Any common origin for the long-term decrease would have to dominate such local effects.

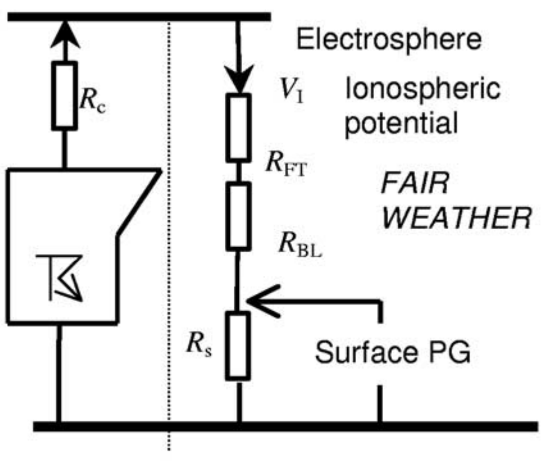

Figure 1. Simplified global atmospheric electric circuit. Thunderstorms separate electric charge, generating a current flowing through an upper atmosphere coupling resistance R_c to the lower ionospheric conductive region, the electrosphere. The ionospheric potential V_I drives a vertical current in the fair weather region of the circuit, through the electrical resistances of the free troposphere R_{FT} and the boundary layer R_{BL}. The measured surface potential gradient (PG) arises from the potential developed across the near-surface resistance, R_s.

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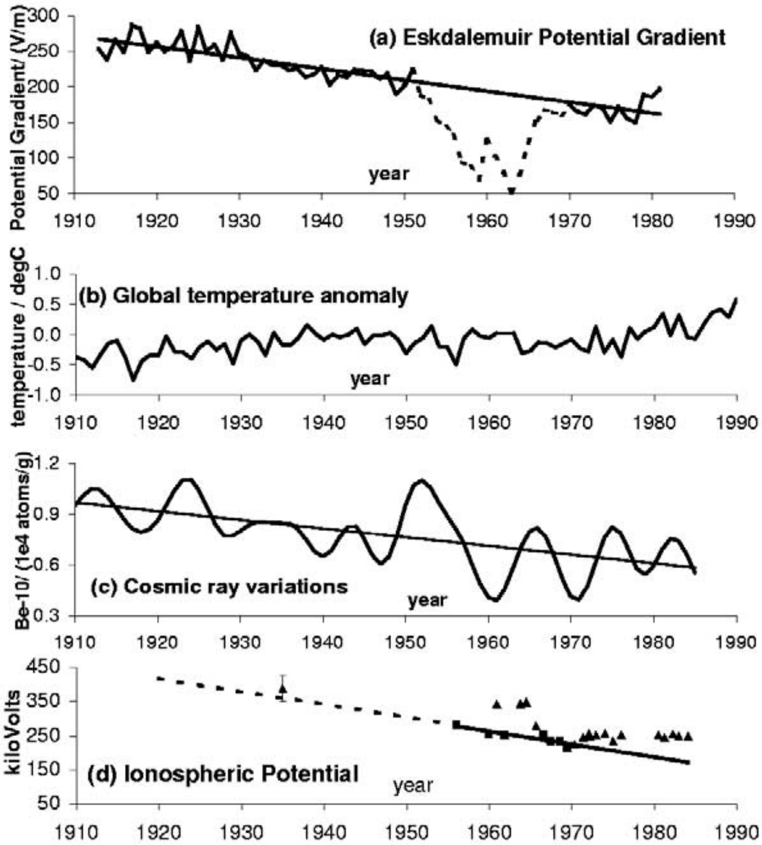

Figure 2. (a) Annual averages of fair weather surface PG, measured at Eskdalemuir, Scotland. (The dotted line marks low PG measurements resulting from ionisation caused by atmospheric nuclear tests.) (b) Global surface temperature anomalies, with respect to the 1960–1990 mean [*Peterson and Vose*, 1997]. (c) Variations of the cosmogenic isotope Be-10 deposited in the Greenland ice core [*Beer*, 2000]. (d) Ionospheric potential measurements [*Markson*, 1985], (squares and triangles) with a trend line estimated. The trend line has been fitted to selected 1956–1970 measurements (squares). (The *Explorer II* result from 1935 was not used in the statistical fit: the point's error bars represent typical variations in the contemporary annual averages of conduction current.)

[4] Figure 2a shows the longer Eskdalemuir fair weather PG time series, from 1911 to 1981. For the period 1920–50 before the weapons testing data gap, the Eskdalemuir PG decreases at 2.2 Vm^{-1} yr^{-1}, with a total PG decrease 1920–50 of 25%. The decrease occurs in all months, but the decline is greatest during the seasonal PG maximum [*Israel*, 1973], averaging 4.0 Vm^{-1} yr^{-1} in February. Between 1920 and 1950, the annual average numbers of fair weather days selected were 84 ± 3 (Lerwick) and 97 ± 16 (Eskdalemuir). Eskdalemuir showed little seasonal variability in its number of fair weather days, but Lerwick had the majority of its fair weather days (33) in the summer months (June, July and August). The summer data at Lerwick shows a decline of 1.4Vm^{-1} yr^{-1}(17%) from 1920–50.

3. Possible Causes of the Potential Gradient Decrease

[5] There are several possible causes for the decline in surface PG including (1) calibration drift in the instruments, (2) local effects causing changes in PG and (3) global changes in the AEC. (1) is most unlikely because of careful standardisation [*Anon*, 1955]. Site and instrument changes were comprehensively reported in the official Observatory Year Books, published annually 1922–1965 [*HMSO*, 1965]. Other than identifying the nuclear weapons period, no systematic effects were found and no land use changes are apparent. (2) could arise from aerosol or ionisation changes. Air conductivity is increased by ionisation and decreased by cloud or aerosol particles, changing the near-surface resistance R_s: surface PG therefore varies inversely with the local air conductivity. Substantial increases in atmospheric ionisation from weapons testing and the nuclear industry only began after 1950 [*Harrison and ApSimon*, 1994], so are not responsible. If the PG decrease arose from aerosol changes, a decrease in aerosol concentration would be required. There is, however, good evidence of an increase in boundary layer particle number concentration. Synoptic meteorological data from Eskdalemuir independently show a decrease in the frequency of days with good visibility [*HMSO*, 1950] and air conductivity measurements in northern hemisphere marine air from 1910–1968 decrease by 32%, 1920–1950 [*Cobb and Wells*, 1970]. A steady local increase in air conductivity is therefore unlikely.

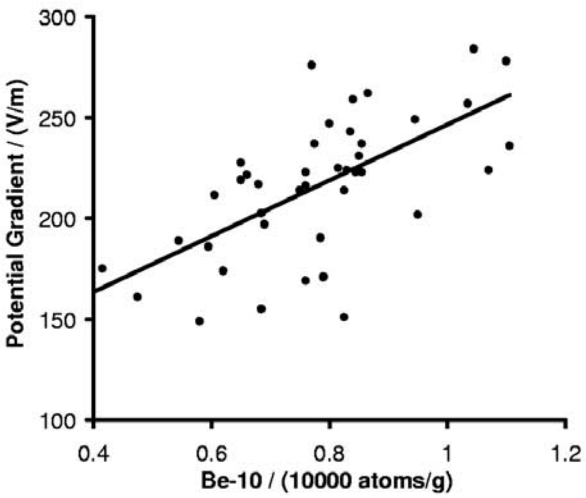

Figure 3. Eskdalemuir potential gradient (volts/metre) 1920–50 compared with the deposited cosmogenic isotope Be-10 (atoms/gramme) in the Greenland ice core, during the period of PG decrease from 1920–50.

[6] A globally-induced change in electrification (3) would result from a decline in current flowing in the AEC. This could arise from either a decrease in charge generation from tropical convective thunderstorms, or a reduction in the thunderstorms' electrical output associated with a change in the thunderstorm-electrosphere resistance R_c [*Markson*, 1981]. A measure of global electrification is the ionospheric potential V_I. Studies of recent changes in surface temperature [*Price*, 1993] show a considerable sensitivity of V_I to global temperature (20% increase in V_I for a 3K change in global temperature): global temperature anomalies using land stations [*Peterson and Vose*, 1997] are plotted for comparison in Figure 2b. There is a negative correlation between the Eskdalemuir PG and global surface temperature anomalies for 1920–50 ($r = -0.55$, $P < 0.002$). It indicates that the PG decreased as the global temperature increased. This is surprising, given the usual assumption of increased thunderstorm activity associated with global warming. Surface temperature changes alone therefore cannot explain the long-term decrease in atmospheric electrification.

4. Secular Cosmic Ray Decrease and the Atmospheric Electrical Circuit

[7] Global thunderstorm charge-exchange maintains the ionospheric potential V_I, but a small modulation in V_I occurs from cosmic ray (CR) variations. A 15% increase in V_I for a 10% increase in neutron count rate at Mt Washington has been associated with changes in R_c occurring above tropical thunderstorms [*Markson*, 1981]. A secular change in CR may therefore be consistent with a PG decrease by a similar mechanism. There are no direct measurements of CR as a continuous time-series from 1920–50, but cosmogenic isotope Beryllium-10 in Greenland ice cores [*Beer*, 2000] indicates a global CR reduction. The reduction in Be-10 from 1920–50 is 34%, Figure 2c. The solar cycle modulation in Figure 2c is principally due to the high latitude effects: modulation of CR at low latitudes, where the AEC would be influenced, is therefore considerably reduced as only higher energy cosmic rays penetrate. Although the ice core was extracted at 65°N, high latitude cosmic ray decreases could not directly reduce the Eskdalemuir PG, as R_s and the PG would increase. (This direct effect is apparent from a weak inverse correlation between CR and the detrended Eskdalemuir PG data.) A CR reduction can therefore only cause a decline in surface PG by decreasing the current flowing in the AEC. The maximum CR effect would be expected when the major global thunderstorm area migrates away from the geomagnetic equator, permitting sufficient atmospheric CR penetration to modulate R_c. This explains the maximum Eskdalemuir decrease during the northern hemisphere winter, when the African thunderstorm generator is considerably south of the geomagnetic equator.

[8] An estimate of the cosmic ray change to the AEC can be found from the CR changes at Mt Washington [*Markson*, 1981]. The Be-10 deposited results from a combination of direct local deposition and atmospheric transport of Be-10 produced globally, in approximately equal proportions [*Beer*, 2000]. The predicted decrease in ionospheric potential 1920–50, assuming the same sensitivity of 1.5 to the 17% global CR change, would be 26%. This is comparable with the PG decrease observed at Eskdalemuir (25%).

[9] There is some experimental evidence for a decline in the ionospheric potential. Direct measurements began in 1956, with a decrease in V_I reported [*Markson*, 1976] between 1956 and 1974. Anomalously high values of V_I occurred in 1961 and 1964, probably associated with reduction of R_c arising from stratospheric nuclear weapon ionisation. (The surface ionisation from atmospheric weapons testing decreased the PG. This, and effects of the 1961–62 testing moratorium, are apparent in the dotted region in Figure 2a). Figure 2d shows the V_I values [*Markson*, 1985], from soundings corrected using the *Carnegie* diurnal variation. The 1961–64 anomalies are plotted as triangles. Since the mid-1970s, V_I stabilised and now has a typical value of 250kV [*Markson and Price*, 1999]. This suggests that the V_I response to the continued CR reduction became dominated by a different effect. Using only the non-nuclear testing 1956–70 values when the trend is apparent (plotted as squares), the trend in V_I was -3.8 kV.year^{-1}. This would correspond to a 27% reduction in V_I 1920–50. Although not used in fitting the trend, this rate of reduction is corroborated by an early ionospheric potential measurement found by the 1935 *Explorer II* stratospheric balloon ascent [*Israel*, 1973]. The 1920–50 CR-induced reduction in V_I, measured V_I trend, and surface PG trend are therefore all quantitatively consistent.

[10] Figure 3 shows a regression between the Eskdalemuir PG and cosmogenic Be-10. There is a statistically significant relationship, with correlation between PG (1920–50) and Be-10 of $r = 0.56$ ($P < 0.0013$). If the additional data from the post-weapons period (1971–81) is included, the PG-Be-10 correlation is increased further ($r = 0.68$, $P < 1 \times 10^{-5}$), indicating a continued decline through the 1951–70 data gap.

5. Discussion

[11] It is clear that there has been a reduction in the atmospheric PG 1920–1970, which is quantitatively asso-

ciated with a reduction in cosmic rays. The long-term reduction in current in the AEC will have influenced fair weather atmospheric electricity parameters and the atmospheric processes linked to ions and charged aerosol [*Harrison*, 2000].

[12] The decline in the PG continued until the mid-1970s, soon after which the PG data ceased to be recorded. At about the same time, however, V_I became relatively constant, despite a continued reduction in CR. The reduction in V_I would have been expected to continue. An explanation for this may lie in the positive response between V_I and surface temperature, at a time of an increase in global temperature. Temperature-induced increases in convection, increasing V_I, may have compensated for the continued reduction from cosmic rays.

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