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Review article

The global electrical circuit: A review

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ABSTRACT

Research topics on the global electrical circuit are addressed that have received attention in recent years. These topics include the diurnal variation of the global circuit, surface measurements of electric field at high latitude, the annual variation, the semiannual variation, the role of lightning as a source for the global circuit, the electrical contribution of mesoscale convective systems, the possible effect of thunderstorms on the E and F regions of the ionosphere, the evidence for a global circuit impact from nuclear weapons tests, the controversy over long-term variations, the response to climate change, and finally the impact of the global circuit on climate.

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1. Introduction

The global electrical circuit is established by the naturally occurring presence of a thin veneer of insulating air (our atmosphere) sandwiched between the conductive Earth and the conductive mesosphere/ionosphere (e.g., Roble and Tzur, 1986; Williams, 2003a; Markson, 2007). This geometry provides for both the spherical capacitor of the DC global circuit and ionospheric potential, and the electromagnetic waveguide of the AC global circuit and Schumann resonances. This review will address both aspects, but will concentrate on the DC global circuit.

2. The diurnal variation of the global circuit in universal time

An early well-known supportive test of C.T.R. Wilson's (1920) global circuit hypothesis was the comparison of the climatology of daily shipboard observations of the surface electric field in clean ocean air, now known as the "Carnegie curve" (Israel, 1973a,b), with the worldwide climatology of thunder days, both in universal time (Whipple, 1929). As new global observations become available, renewed attention has been given to the mismatch between these two curves. Simpson (1929) had addressed the disagreement initially in his opposition to C.T.R. Wilson's (1920) positive dipole, now known to be correct (See Williams (2009-this issue) for an historical discussion of the Simpson-Wilson debate) Williams and Heckman (1993) called attention to the substantial differences in the amplitude variation of the two curves (shown more recently by Bailey et al., 2007), supporting ideas originating with Wilson (1920), and substantiated by Wormell (1930, 1953) (and others) that currents between electrified clouds and ground other than lightning dominate the DC global circuit. (Recent studies by Hayakawa et al. (2005) and Nickolaenko et al. (2006) have overlooked these well established earlier findings, and as a consequence have misinterpreted their observations of global lightning in the context of the DC global circuit.)

More recently, attention has been given to a clear difference in the shape of these two well-known curves of atmospheric electricity. In the Carnegie curve, the Americas dominate, and in the thunder day curve, Africa dominates. The latter result was firmly substantiated in lightning observations from space with the Optical Transient Detector (OTD) (Christian et al., 2003) and the Lightning Imaging Sensor (LIS) (Williams and Satori, 2004). More recent work by Bailey et al. (2007) substantiates these earlier results with optical observations from space. Williams and Satori examined both combined OTD/LIS data and Schumann resonance observations. Africa is also the lightning "winner" in the SR observations. African lightning has been shown to dominate South American lightning most of the time (Williams, 2005). Two explanations have appeared to account for the Carnegie curve discrepancy — Williams and Satori (2004) and Kartalev et al. (2006). The explanation in Williams and Satori (2004) rests on Wilson's (1920) inference, often overlooked, that electrified shower clouds are of comparable importance to thunderclouds in supplying current to the global circuit. South America exhibits less lightning but more rain than Africa, by a substantial margin, and so by inference, a greater abundance of electrified shower clouds, and consequently a stronger relative contribution to the Carnegie curve.

The explanation by Kartalev et al. (2006) is notably different. It does not rely on differences in intrinsic "chimney" sources but rather on the role of the magnetic dip equator in preferentially guiding source current. The claim is made based on model calculations, that the Carnegie curve is dominated by sources within +/−11° of the dip equator, which meanders considerably in latitude relative to the geographic equator. This study does not address the alternative hypothesis discussed above, so the author will take this opportunity to critique the alternative. Firstly, there is now substantial evidence, beginning with Wilson (1920), that lightning is not the primary source current for the DC global circuit. Yet lightning is used here as a measure for that. Secondly, despite numerous theoretical calculations (Kasemir, 1952, 1959) and modeling studies (Tzur and Roble, 1985; Stansbery et al., 1993; Kartalev et al., 2006), there is still much uncertainty and lack of agreement about the fate of the current from electrified clouds above the equalization layer near 65 km altitude (Israel, 1973a,b). Thirdly, this study makes specific predictions for the effective seasonal variation of the three major tropical chimneys to the Carnegie curve. These predictions (and the global maps of the magnetic dip equator relative to lightning) show dramatic seasonal variations. For example, the ratio of America to Asia/Oceania (otherwise known as the Maritime Continent) changes by an order of magnitude. The America/Africa ratio changes by a factor-of-two. Published seasonal variations of the Carnegie curve (Torreson et al., 1946) and seasonal variations of electric field recorded at Vostok, Antarctica (Burns et al., 2005) (but not addressed by Kartalev et al., 2006), show substantially more seasonal stability than these predictions.

Results on this topic, presented by R. Blakeslee at the recent International Conference on Atmospheric Electricity in Beijing (and shown independently by Z. Kawasaki), shed further insight on the "discrepancy" between the Carnegie curve and the original curve of thunder days by Brooks (1925). In this analysis, the global lightning according to the optical observations from space is consistent with the Carnegie curve in showing a maximum near 19–20 UT (when South America is most active), rather than at 14–15 UT (when Africa is most active). Analysis of the various contributions to the integrated curve shows however that this result is not caused by South America dominance over Africa, but rather by a pronounced "tail" for the lightning activity in the Maritime Continent, i.e., sustained activity after its maximum contribution near 8–9 UT. This lightning may be the result of oceanic flashes within the Maritime Continent, set off in convection set up by land breezes, and which would not be well represented in the thunder day data because the lightning is too far from meteorological observing stations over land. These speculations remain to be verified with the same data set.

3. Surface-based measurements of the global circuit at high latitude

Much recent progress has been achieved in the measurement of the global circuit at high latitude (Frank-Kamenetsky et al., 2001; Reddell et al., 2004; Burns et al., 2005). The advantage of high latitudes and low temperature is a stably stratified boundary layer (the surface is colder than the air above it), a situation that eliminates to a large degree the local fluctuations common at temperate latitudes that strongly interfere with the global signal. Simpson (1905) was the pioneer in efforts to measure atmospheric electricity at high latitude. His diurnal curve based on a full year of daily measurements at Karasjok, Lapland is remarkably similar to the Carnegie curve in phase when replotted in universal time, though Simpson was not aware of this fact till much later (Simpson, 1949).

The recent work to monitor the global circuit from the ground has been carried out in Antarctica, at Vostok (Frank-Kamenetsky et al., 2001; Burns et al., 2005) and at the South Pole (Reddell et al., 2004). Much attention has been given at both sites to the diurnal variations of the electric field in universal time, for comparison with the classical Carnegie curve (Whipple, 1929; Israel, 1973a,b). Despite the meteorological advantages in polar regions for monitoring the global circuit, the presence of a second generator there has long been recognized (Park, 1976). The interaction of the solar wind and the Earth's magnetic field causes a dawn-to-dusk potential difference across the polar cap that contributes to the vertical electric field at the surface. The recent breakthrough in Antarctica work has been the successful removal of the latter effect from the electric field records at the South Pole (Reddell et al., 2004) and at Vostok (Corney et al., 2003; Burns et al., 2005). The residual signal, when multiple days are averaged together, bears a strong resemblance to the Carnegie curve in both amplitude and phase. The polar cap potentials are greater for the South Pole station, are more substantial than for Vostok, and can be seen by comparing uncorrected measurements in Bering et al. (1998) with the later corrected records (Reddell et al., 2004).

The need for careful selection of “clean” days and the integration of many days (two months in Burns et al. (2005) and three months in Reddell et al. (2004) to bring out the characteristic unitary variation of the Carnegie curve cannot be overemphasized. In this sense, the results achieved in Antarctica are on a par with the measurements by the Carnegie Institution (Parkinson and Torreson, 1931; Torreson et al., 1946) over the world's oceans, in clean air. Daily records in both sets of measurements show significant departures from the Carnegie curve, and are generally not shown in the published papers. The only way to determine whether such departures are truly global in nature is to have simultaneous records at distant sites, showing correlated behavior. Historically, highly correlated behavior between distant measurement sites on individual days has been more likely with measurements of ionospheric potential (Muhleisen, 1971; Markson et al., 1999) than with local measurements of electric field or air-earth current density. In earlier work (Holzworth et al., 1984; Norville and Holzworth, 1987)) in which correlated measurements of electric field were achieved at distant locations on individual days, similarities with the Carnegie curve were also documented. Attempts to monitor the DC global circuit in local measurements need to coordinate among multiple sites toward establishing truly global variations on all time scales.

4. The annual variation of the DC global circuit

The establishment of the variation of the DC global circuit on the annual time scale has been tortuous, historically. Lord Kelvin, C.T.R. Wilson and G.C. Simpson seemed content with a NH winter maximum in potential gradient, but did not interpret this as a global signal (Kelvin, 1860; Wilson, 1903; Simpson, 1905). The apparent contradiction between this result and the maximizing of global thunderstorms in NH summer was first addressed by Whipple (1929), but without resolution. Modern well-sampled observations of lightning from space (Christian et al., 2003) and measurements of the intensity of the Earth's Schumann resonances (Sátori et al., 1999; Sátori et al., 2008) are consistent with Whipple's findings regarding thunder days, and leave little doubt about the NH summer maximum in global lightning activity.

This contradiction in the phase of the annual variation was resolved by Adlerman and Williams (1996), who assembled published seasonal variations of electric field and conductivity from both hemispheres, and showed that the field maximum in local winter was a local effect of enhanced aerosol. Recent work in this area appears in Kubicki et al. (2007). The diminished electrical conductivity causes an enhanced electric field to guarantee continuity of fair weather conduction current. A reanalysis of the complete set of Carnegie observations over the oceans in that study also showed a NH summer maximum. Surface electric field measurements at high latitudes (Reddell et al., 2004; Burns et al., 2005) (where the air is presumably sufficiently clean so as not to impose local conductivity variations, though more investigation is warranted here) also show consistent maxima in NH summer. As noted by Adlerman and Williams (1996), many local measurements of air-earth current (which provides some immunity to local conductivity variations) show the same annual phase (see also Retalis, 1981). Finally, and perhaps most importantly, a reanalysis of all available measurements of ionospheric potential (Markson, 2007) shows a consistent result on the annual variation, with maximum in NH summer.

It is important to note that despite the similarity in phase between global lightning and the DC global circuit, the annual amplitude variation of global lightning is substantially greater than the conventional measures of the global circuit. The lightning variation recorded by Christian et al. (2003) from space and from the Earth's surface in Schumann resonance measurements (Sátori et al., 1999) is a factor-of-two, but the variations in surface electric field (28%; Burns et al., 2005), air-earth current (23%; Retalis, 1981) and ionospheric potential (21%; Markson, 2007) are all substantially less. A similar result has been noted on the diurnal time scale: global lightning is more volatile and variable than the “DC” current sources (point discharge current and precipitation current) that dominate the global circuit (Wormell, 1930, 1953).

The annual variation of the global circuit with northern hemisphere summer maximum is attributable to the asymmetry in land mass between the northern and southern hemispheres and the global variation in air temperature that accompanies that asymmetry (Williams, 1994; Reddell et al., 2004).

5. The semiannual variation of the global circuit

Tropical convection is enhanced twice per year, particularly over continental areas where electrified weather is most prevalent, by the Sun's equinoxial crossings of the equatorial region (Williams, 1994). The associated variation in near surface air temperature is subtle (~1 °C), but the effects are substantial. Clear semiannual signals are apparent in many surface measurements of air-earth current (Hogg, 1950; Williams, 1994; Adlerman and Williams, 1996). In more recent analysis, a semiannual signal is evident in the surface electric field at Vostok, Antarctica (Burns et al., 2005, Table 5) and in the climatology of ionospheric potential (Williams, 1994; Markson, 2007). In assessing the presence of a semiannual signal, it is important to note that for two superimposed sinusoidal variations, one annual and one semiannual, the distinct double peaks arising from the semiannual contribution disappear when the amplitude of the semiannual variation is less than 1/4 of the annual variation.

In contrast to the measurements with the semiannual character cited above, global lightning as an integral over the year (Christian et al., 2003) shows no double-peaked behavior near equinoxes. The semiannual signal can only be seen if lightning at low latitude is integrated (Christian et al., 2003). The presence of a substantial semiannual signal in traditional measurements of the DC global circuit (air-earth current and ionospheric potential) is further evidence that the source currents for the DC global circuit are relatively more concentrated in the tropics than in temperate zones. Stated another way, the ratio of non-lightning source current to lightning source current to the global circuit is increasing toward the equator. This conclusion is consistent with Wilson's (1920) emphasis on electrified shower clouds and inferences drawn for Africa and South America on the diurnal time scale (Williams and Satori, 2004), as discussed in Section 2.

6. The role of lightning in the DC global circuit

The modern literature on the global circuit is replete with the idea that thunderstorms are the main current source (Wallace and Hobbs, 1977; Williams, 1988; Blakeslee et al., 1989; Bering et al., 1998; Rycroft et al., 2000; Holzworth et al., 2005; Hayakawa et al., 2005; Kartalev et al., 2006; Nickolaenko et al., 2006), despite Wilson's (1920) additional emphasis on electrified shower clouds. Some recent studies have gone so far as to claim that the main source current for the global circuit is lightning (Bering et al., 1998). The reason for this lopsided emphasis today is undoubtedly historical. The routine thunder day observation documents thunderstorms and lightning, and no routine observation has been available for “electrified cloud without lightning”, and so this important latter entity went by the wayside. It is increasingly recognized however, as this review attempts to show, that the electrified shower clouds are essential in explaining many aspects of the global circuit (Williams and Heckman, 1993; Füllekrug et al., 1999), including the American dominance over Africa in the Carnegie curve (Williams and Satori, 2004), the prominent semiannual signal, and the general flatness of the variation of the DC global circuit on many time scales. A recent study by Rycroft et al. (2007) presents additional evidence that lightning is a secondary player in the DC global circuit.

Holzworth et al. (2005) have compared lightning activity recorded on the World Wide Lightning Location Network (Dowden et al., 2002) and vertical current density measured from balloons in the stratosphere (in the South Polar region), and find correlated behavior. The agreement between balloon measurements and the detailed phase information on the diurnal time scale are however not addressed, and the amplitude variations in current density are larger than what one expects for globally representative signals. Earlier balloon measurements of a similar nature by Holzworth et al. (1984) did not show these large diurnal variations in Jz. Based on recent measurements of Jz on the ground at a high latitude station (Michnowski et al., 2007; Kozyreva et al., 2007), the vertical current has a substantial contribution from the magnetosphere. Michnowski states: “The Ez and Jz behavior is much more variable and complicated in high latitude zones than in the middle and low ones.” In the very early measurements of Ez at high latitude (Lapland), Simpson (1905) recorded a diurnal amplitude variation of the field which is more than twice that of the Carnegie curve measured over the world's oceans at low latitude.

Troshichev et al. (2004) have also made comparisons between the electric field measurements at Vostok, Antarctica and global measurements of large lightning transients detected by ELF methods. Little correlation between the two data sets was found. Though this result could be interpreted as evidence that the primary source current for the DC global circuit is not lightning, it should also be pointed out that this particular lightning type (“mesoscale” lightning; Williams, 1998; Williams et al., 1999; Williams and Yair, 2006) is likely to have a very different diurnal variation than the ordinary lightning dominating in the local afternoon over land. In the same context, it is worth emphasizing that the integrated Wilson current contributions above thunderstorms showed proportionality to the total lightning flash rates of those storms (Blakeslee et al., 1989), evidence that the “DC” and “AC” global circuits are positively correlated.

Lightning with extraordinary characteristics is now recognized to cause luminous phenomena (sprite, elves and haloes) in the middle atmosphere. The extraordinary characteristics include charge moment, peak current, and peak continuing current. The contribution of this outlier lightning to the DC global circuit has been considered (Füllekrug, 2004; Füllekrug and Rycroft, 2006; Rycroft et al., 2007). Despite the extraordinary characteristics, the total numbers of these special lightning flashes is small (one in ten thousand flashes), and so their contribution to the global circuit (a negative contribution for the giant positive flashes) is generally small (<1%).

7. The contribution of mesoscale convective systems to the global circuit

Isolated thunderstorms and electrified convective clouds have long been viewed as the main sources for the global circuit. Recent work (Davydenko et al., 2004; Stolzenburg et al., 2007) has given attention to the role of mesoscale convective systems (MCSs) (squall lines with trailing stratiform regions of precipitation). Model calculations have shown that the Wilson current contribution of an MCS can be 1–2 orders of magnitude larger than that from an ordinary thundercloud, primarily because of the large areal extent of the MCS. This finding must be balanced by the result that there are far fewer MCSs than ordinary thunderstorms. To take the extreme case of the largest MCS, the Mesoscale Convective Complex (MCC), typically there is only one such storm in progress globally at any given time (Laing and Fritsch, 1997).

One complication in the evaluation of the contribution of MCSs to the global circuit is their variable charge structure. Type A and Type B MCSs have been identified (Marshall and Rust, 1993). Their evaluated current contributions to the global circuit have opposite sign. The global contribution will require further study of the MCS types found in various regions of the globe.

One meteorological aspect of MCSs that is well established is their lag in the local diurnal cycle relative to ordinary thunderstorms. This diurnal phase shift is evident in the production of giant Q-bursts (Williams et al., 1999) often produced in the stratiform region of the MCS (Williams, 1998; Williams and Yair, 2006). This diurnal shift is a consequence of the mechanism of organization of MCSs which frequently involves an amalgamation of initially isolated convective cells, and so frequently the MCS activity is delayed relative to the afternoon thunderstorms. This diurnal phase shift needs to be considered in the evaluation of the contribution of MCSs globally to the Carnegie curve of atmospheric electricity (Chalmers, 1967).

8. Global circuit effects in the E and F regions of the ionosphere?

Recent studies by Immel et al. (2006) and England et al. (2006) have revealed a pronounced longitudinal variation in the equatorial structure of the E and F region ionosphere. This longitudinal structure mirrors the wavenumber-4 structure of the tropical continental “chimneys”, with maximum enhancements over the Americas, Africa and the Maritime Continent, and with a fourth maximum over the Pacific Ocean. This finding is peculiar in the global circuit context, as the conventional thinking is that electrified weather in the troposphere is largely decoupled from the upper regions of the ionosphere. Recently established perturbations in ionization by lightning — sprites and elves — are believed to affect only the D region of the ionosphere (Füllekrug et al., 2006), not the E and F regions.

Preliminary interpretations of the wavenumber-4 observations in the upper ionosphere (England et al., 2006) are based on tidal forcing originating in tropospheric weather. This explanation provides for four perturbation maxima in longitude. It has recently been established however (Smith et al., 2005) that gamma radiation originating in the upper portion of thunderstorms (Williams et al., 2006) is also modulated in longitude by the presence of the continental chimneys (Smith et al., 2005) separated by roughly 90° in longitude, in a wavenumber-4 structure. Is it possible that X-ray and gamma ray ionization is responsible for the structure documented by Immel et al. (2006)?

One test of this idea is to follow the seasonal variation of the ionospheric perturbations, as it is well established that lightning centers in tropical chimneys migrate westward in NH summer, on account of the shapes of the continents at low latitudes. The space-time resolution of the published observations is not adequate at present to perform these tests.

9. Global effects of nuclear weapons tests

Previous research on the global electrical circuit has shown that the ionospheric potential, the preferred measure, represents an integral of electrified tropospheric convection worldwide. Perhaps the most provocative recent finding in global circuit work is the evidence that the extensive atmospheric testing of nuclear weapons in the mid-twentieth century had a substantial effect on the ionospheric potential (Markson, 2007). The global effect of testing on the Earth-ionospheric waveguide had been recognized almost immediately by virtue of its effect on communication (Williams, 1962; Kenney and Willard, 1963; Zmuda et al., 1963; Madden and Thompson, 1965). Furthermore, local electrical effects of radioactive fallout near the Earth's surface over land have long been recognized and reported (Harris, 1955; Simon, 1962; Agarwala, 1964; Pierce 1972a,b; Collingbourne, 1972; Harrison, 2004a,b; Harrison and Ingram, 2005). The local interpretation of these latter observations is emphasized in a statement by Pierce (1972a,b):

> “The electrospheric potential V_H is controlled by thunderstorm activity; there is no obvious way that it can be significantly influenced by fallout”.

Markson's idea (2007) for control of ionospheric potential is based on the worldwide radioactive fallout in the stratosphere (Bennett, 2002; Simon et al., 2006) rather than the near surface. Originating from nuclear tests at high altitude (stratosphere and mesosphere), the radioactive aerosol accumulates in the lower stratosphere (Glasstone and Dolan, 1977; Simon et al., 2006) where the residence time of the debris is 3–4 years (Bennett, 2002). (The long residence time for aerosol in the stratosphere was also manifest by the volcanic eruption of Mt. Pinatubo in the Philippine Islands in 1991 which had the effect of temporarily reducing global temperature (Hansen et al., 1992)). The physical interpretation is that enhanced conductivity over electrified clouds at high levels is enhancing the supply current to the global circuit, while leaving a substantially smaller effect in the return path in fair weather regions. A similar idea was advanced earlier to account for solar (Markson, 1978) and cosmic ray (Markson, 1981) modulation of the global circuit.

The inferred enhancements in the global circuit identified by Markson (2007) are found in the elevated values of ionospheric potential by R. Muhleisen in the 1960s, when some measured values (500 kV) were twice the mean value (240 kV) (Muhleisen, 1977). The elevated V_i values are well correlated with independent estimates of the stratospheric burden of radioactivity resulting from the weapons tests (Glasstone and Dolan, 1977). Muhleisen himself was well aware of his large numbers (Muhleisen, 1977) in that era, but made an interpretation based on the 11-year solar cycle. Markson's interpretation is more plausible.

Problems remain with a quantitative interpretation: theoretical models for the enhancement of supply current to the global circuit (Holzer and Saxon, 1952; Willett, 1979), where conductive upper boundaries are imposed (to replicate the stratospheric radioactive debris) fall short in accounting for the necessary increase in source current (and ionospheric potential) by at least a factor of three. (Coincidently, enhanced rainfall (Nicholson et al., 1999), Congo River discharge (Bultot and Dupriez, 1987; Price and Asfur, 2006) and inferred lightning activity (Price and Asfur, 2006) were also documented in the 1960s over Africa. These positive anomalies may have contributed to the high values of ionospheric potential record by Muhleisen in the same period.)

Other measurements of the global circuit during the period of intensive weapons testing can also be found in the literature (G. Bering, personal communication, 2008). Stratospheric conductivity measurements in Australia by Paltridge (1965) on November 20, 1964, during the downturn in the inferred global stratospheric radioactivity burden shown in Markson (2007), do not show particular evidence for anomalously high conductivity. Furthermore, the product of electric field at 16 km (Paltridge, 1964) and total conductivity at 16 km altitude (Paltridge, 1965) is ~3 pA/m^2, not anomalously large.

Despite these problems with quantitative model verification and local verification, the validity of the global impact of the weapons tests is strengthened by published results on air-earth current for Athens (Märcz and Harrison, 2005) and for Kew Observatory (Harrison and Ingram, 2005). The latter measurements shed new light on earlier findings for Kew by Collingbourne (1972) in which evidence for a global signal is also apparent. Air-earth current is widely recognized to be more globally representative than the surface electric field (Märcz and Harrison, 2005). The enhancements in air-earth current at both locations exceed a factor-of-two (consistent with the substantial increases in V_i) and are well-timed with the stratospheric emplacement of radioactivity. Local enhancement in the conductivity of surface air by radioactive fallout is not by itself expected to increase the air-earth current, consistent with the earlier interpretation of Pierce (1972a,b) and with the behavior of natural surface radioactivity (Israelsson and Tammet, 2001).

Markson's plot of stratospheric burden of radioactivity declines by two orders of magnitude in the 1980s from its peak in 1963. The evidence for the short residence time (~30 days) for radioactive debris in the troposphere (Bennett, 2002) is then consistent with the global assessment of Cobb and Wells (1970): “It appears that radioactive contamination of the free atmosphere has returned to a reasonably normal level which is not detectable as a similar increase in the electrical conductivity.”

Markson uncovered the evidence for a global circuit effect of weapons tests in studying the long-term stability of the global circuit, as reflected in V_i variations. His summary of all V_i measurements show no significant trend with time. These findings resolve earlier (unpublished) puzzlements (Williams and Renno, 1991) with a declining trend in the global circuit, revisited more recently by Märcz and Harrison (2005). A critical discussion of additional published evidence for a decline in the global circuit is addressed in the next Section 10.

10. Is the global circuit declining with time?

The global circuit, as an integrator of electrified weather worldwide, provides a natural framework for studying global change. Much attention has been given recently to long-term changes in the global circuit. This section reviews the many contributions to this topic, a controversial area.

10.1. Harrison (2002, Geophysical Research Letters)

Harrison (2002) initiated the idea that the electric field in the atmosphere was undergoing a long-term decline based on the record of electric field at a single land station (Eskdalemuir, Scotland), spanning the period 1911–1981.

10.2. Williams (2003b, Geophysical Research Letters)

Williams interpreted the results of Harrison (2002) as a local aerosol effect, with the aerosol serving to reduce the electrical conductivity and as a consequence, increase the electric field in the polluted earlier portion of the 20th century. Numerous subsequent publications have appeared with a bearing on the long-term trend of the global circuit, and these studies are critically reviewed below. Harrison (2003a,b) replied to the suggestion but continued to support the observed decline as a global effect.

10.3. Märcz and Harrison (2003, Annales Geophysicae)

Märcz and Harrison (2003) have documented a long-term decline in electric field at Nagycenk, Hungary. They argue that this decline is consistent with the earlier report by Harrison (2002) that the global circuit is declining over the past century.

10.4. Williams et al. (2005, Geophysical Research Letters)

Williams et al. (2005) have shown evidence that the long-term decline in electric field at Nagycenk, Hungary documented by Märcz and Harrison (2003) can be explained by the shielding effects of trees that have monotonically heightened over the period of the record. Electric field measurements were undertaken away from a forest edge in Weston, Massachusetts to quantify the shielding effects of trees, which were shown to behave like good conductors in comparison model calculations.

10.5. Harrison (2004a, Atmospheric Research)

This study gives additional attention to the record of electric field at Eskdalemuir. Seasonal variations of smoke concentrations (based on measurements over the period 1948–1955 by McIntosh (1957)) are examined and a factor-of-three change is noted between summer (minimum) and winter (maximum), supporting the idea that aerosol variation is dominating the local seasonal variation of electric field at many land stations (Adlerman and Williams (1996), rather than the global circuit.

Monthly mean diurnal variations are also examined and bear some resemblance to the Carnegie curve of atmospheric electricity (Israel, 1973a,b; Table XIX). In winter months, the correlation coefficient between the Eskdalemuir curves and the Carnegie curve reaches 0.8. It is likely that the wintertime correlations are highest because of the stratified boundary layer more common in winter. The glimpse of the global circuit variation on the (integrated) diurnal time scale is however no guarantee for globally representative data on longer time scales as claimed by Harrison (2003a,b).

Comparisons are also made between Eskdalemuir and the Carnegie measurements on the same days (and over the same hours) in the short period 1928–29 when overlapping records are available. Some correlation is evident again on the diurnal time scale, but again this is no guarantee for globally representative data on longer time scales. The claim made elsewhere (Harrison, 2004b) in this context: “The 20th century decline is however, also apparent in oceanic measurements of PG” (Harrison, 2004a) is invalidated by fundamental aliasing problems. As noted by Harrison (2004b), the absolute values of electric field between the ocean and land measurements differ appreciably (more than a factor-of-two), and this difference is attributable to well established differences in aerosol and associated air conductivity, as is also discussed in the summary (in Section 10.7) of Harrison (2007).

10.6. Harrison and Ingram (2005, Atmospheric Research)

This study examines the long-term record of air-earth current at Kew, near London. Jz is a surface measurement widely recognized to be more globally representative than the electric field (Märcz and Harrison, 2005). The uninterrupted monthly record of Jz from 1912 to 1940 in Harrison and Ingram (2005) is generally flat with time (despite documented variations in electric field and conductivity over the same time period), and shows no decline over the same period that Harrison (2002, 2004a) showed a decline in electric field at Eskdalemuir, inferred in the latter study to be a global signal.

The record of Jz at Kew during the later period (1957–1978) shows a dramatically different behavior that has also been used by Märcz and Harrison (2005) to support a long-term decline in the global circuit. Other interpretations have been offered (see Section 9). This later portion of the Jz record is also discussed in the section on Markson (2007) below.

10.7. Harrison (2007, Atmospheric Research)

Toward further examination of his initial hypothesis (Harrison, 2002) that Eskdalemuir, Scotland is a suitable site to monitor long-term changes in the global circuit, Harrison (2007) examined newly uncovered information on electrical conductivity of surface air for the period 1909–1911. He uses the conductivity value with previously available values for electric field at Eskdalemuir (234 V/m) to compute the vertical current density, and then compares these values to the situation at a demonstrably polluted site (Kew, near London) and to clean conditions over oceans during the Carnegie Cruise. On the basis of these Jz comparisons, the author concludes: “The air conductivity is sufficiently large to show quantitatively that Eskdalemuir in 1911 was an unpolluted site”.

This conclusion is questionable. The appropriate quantity to examine in judging the cleanliness of the local air is not Jz, but the electrical conductivity itself. (In the earlier hierarchy of global representativeness (Märcz and Harrison, 2005), one has ionospheric potential, current density, electric field and lastly conductivity as the most “local” measure. Table 1 compares values for total conductivity at various locations, including the values identified by Harrison (2007) for Eskdalemuir. (Conductivity values for the oceanic boundary layer, where the air is often least polluted, are conspicuously absent from Harrison's study.)

Table 1
Total conductivity of surface air

Location	Reference	Conductivity (fS/m)
Marsta Obs., Sweden	Israelsson and Tammet (2001)	47
Oceans	Cobb and Wells (1970)	30
Peebles, Scotland	Harrison (2007)	13
Eskdalemuir, Scotland	Harrison (2007)	9.8
Edinburgh, Scotland	Harrison (2007)	5.1
Kew, England	Harrison (2007)	3.8

As expected, the conductivity values at all land stations except one (all reasonably close to sea level) are substantially smaller than the ocean value, a result attributable to polluted conditions over land (Israel, 1973a,b). Kew, near London, one of the most densely populated cities in the world, has heavily polluted air and the lowest conductivity. At Kew, Harrison and Aplin (2002) have concluded that the variation of electric field is dominated by changes in air conductivity. More important to the issue at hand, the oceanic value (Cobb and Wells, 1970) is more than three times the value for Eskdalemuir provided by Harrison (2007). (This conductivity contrast may have actually increased following the period 1909–1911 in light of evidence in Novakov et al. (2003) for a growing pollution load over the United Kingdom following this time.). As noted earlier (Williams, 2003b), the factor-of-three contrast in conductivity is in all likelihood the explanation for the large electric field at Eskdalemuir during this period—nearly twice the mean oceanic values (Israel, 1973a,b) of 130 V/m.

(At some land stations, the electrical conductivity is influenced by surface radioactivity, in addition to aerosol. One good example is the Marsta Observatory in Sweden (Israelsson and Tammet, 2001; Table 1), where the total conductivity 47 fS/m is significantly larger than the ocean values. The mean electric field (51 V/m) at Marsta is also less that half as large as the oceanic value (130 V/m) from the Carnegie cruises (Israel, 1973a,b).)

Harrison (2007) also questions long-term changes in aerosol as an explanation of the long-term changes in electric field on the basis that the visual range measurements there do not show a systematic change (though the observations referred to are not shown). Williams (2003b) cited evidence in this context that the visibility and conductivity of air were not tightly linked. In another recent publication, Harrison (2005) says on this issue: “Particles act most effectively to scatter electromagnetic radiation when the diameter is comparable with the wavelength of the incident radiation, therefore small ions (diameter ~0.2 nm) and ultrafine particles (~50 nm) will not have radiative effects at visible wavelengths”. This statement provides a correct explanation for why changes in electrical conductivity cannot be documented with visibility changes, and weakens the claim (Harrison, 2007) for evidence against long-term changes in air conductivity at Eskdalemuir.

In this examination of surface atmospheric air at Eskdalemuir (Harrison, 2007) the earlier atmospheric electrical work at the same location by Pierce (1972a,b) goes uncited. Pierce had concluded that Eskdalemuir was a polluted site and so unsuitable for studying global variations. Harrison's (2007) values for conductivity reinforce Pierce's earlier conclusion.

Harrison (2007) concludes this study by saying: "Without substantial aerosol loading at the outset of the measurements, the steady decrease of potential gradient at Eskdalemuir observed during the first half of the twentieth century cannot be readily explained in terms of decreasing surface aerosol concentration". In fact, the data on potential gradient at Eskdalemuir shown by Harrison (2004a,b) do not show a significant long-term decline until around 1930, the time when the black soot production in the UK (Novakov et al., 2003) reaches its maximum and begins a long-term decline. Consequently, Harrison's statement is without basis.

10.8. *Märcz and Harrison (2005, Annales Geophysicae)*

In this study, additional local records of atmospheric electricity are examined for trends to support the earlier idea (Harrison, 2002; Märcz and Harrison, 2003) that the global circuit is declining over time. In considering various measures for the global circuit, the following prioritization is given by Märcz and Harrison (2005):

> "For studies of the global circuit, the ionospheric potential is the primary quantity of interest, followed by the air-Earth current density. The potential gradient is then the remaining alternative, measured, in order of desirability, in oceanic air, mountain air, continental rural air, and finally, urban air."

But having made this appropriate prioritization, these authors do not reference the evidence then available for long-term stability of the global circuit in the priority measure ionospheric potential in Markson (1985). If Märcz and Harrison support air-earth current as the measurement of second priority, why do they not call attention to the four-decade record of air-earth current at Kew showing no trend (Harrison and Ingram, 2005), but instead emphasize a shorter segment of the same record (1966–1978) in Märcz and Harrison (2003) that may have an alternative explanation for reasons discussed in Section 9? Not cited in the collection of records from Märcz and Harrison (2005) is the complete (1965–1980) air-earth current record at Athens (Retalis, 1981), in which rigorous statistical analysis showed no significant trend, despite elevated values in the beginning of the record possibly also attributable to effects of weapons tests discussed in Section 9.

If the lowest priority category of potential gradient is providing evidence for a decline in the global circuit (Märcz and Harrison, 2005), rather than providing indications of changes in aerosol loading (Williams, 2003b) or the local growth of trees (Williams et al., 2005), why do other carefully managed records of surface electric field at the NASA Kennedy Space Center (Harrison, 2006) not show a decline with time? A plausible answer: the surface electric field over land is not a reliable means to measure the global circuit, unless considerable care is exercised to minimize local influences (Cobb, 1968; Markson, 1985; Reddell et al., 2004; Burns et al., 2005).

10.9. *Märcz and Harrison (2006, Geophysical Research Letters)*

Märcz and Harrison (2006) object to the conclusion in Williams et al. (2005) that growing trees are the dominant influence in the decline in electric field with time at Nagycenk observatory. They argue that the tree configuration modeled in Williams et al. (2005) for Weston, Massachusetts is inappropriate for the trees at Nagycenk. They also show a set of relative field measurements away from one grove of trees that are interpreted to show a substantially smaller impact of the trees than was inferred by Williams et al. (2005). The calculations in Williams et al. (2005) are admittedly not appropriate for the trees there. In response to this shortcoming, a more detailed electrostatic calculation is presented here. These results lead to a different interpretation of the measurements of Märcz and Harrison (2003) than is presented in Märcz and Harrison (2006), and ultimately lead to the same conclusion drawn in Williams et al. (2005): the growing trees are dominating the decline in electric field at Nagycenk.

The tree configuration at Nagycenk is significantly more complicated than the one measured and modeled in Weston, Massachusetts (Williams et al., 2005). The measurement location for potential gradient at Nagycenk lies between a nearby grove of trees to the east, and a more extended forest to the west. As model calculations will show, both sets of trees contribute significantly to a screening of the fair weather electric field at the measurement location. In Märcz and Harrison (2003), all estimates of distances and heights of trees appear to be rounded to the nearest 5 m, and other key information about the forest to the west was unavailable. More detailed information was needed for the implementation of a more sophisticated electrostatics model toward resolving the main argument raised by Märcz and Harrison (2006). This additional information has been generously provided by Ferenc Märcz in personal communication via electronic mail over the period December 2005–February 2006.

The electrostatic model is again based on a numerical solution of Laplace's equation by the finite element method (D'Alessandro, 2003). The geometry is fully three-dimensional, but in this case possesses a symmetry in the north–south direction about the east–west measurement axis. All calculations of the vertical electric field at ground level are referenced to this east–west axis shown in Märcz and Harrison (2006, Fig. 1). Along this x-axis, the grove of trees to the east (to the left in Fig. 1) is modeled as two lines of trees, one at $x=0$ m and the second at $x=5$ m, each row treated as a vertical "fence" of height 16 m and width 1 m, extending perpendicularly to the x-axis in the north–

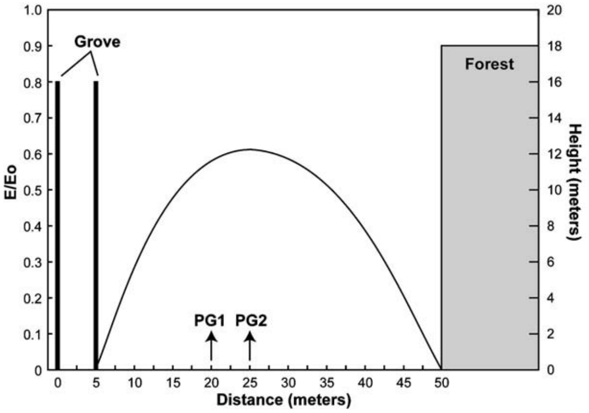

Fig. 1. East–west traverse at the Nagycenk Observatory, showing the locations of measurement sites PG1 and PG2 referenced in Fig. 1 of Märcz and Harrison (2006), the locations of rows of trees (on the left) and a forest edge (on the right), and the results of the electrostatics calculations for the effects of these trees on the uniform ambient electric field E_o.

south direction for +/−12.5 m. The extended forest to the west (on the right hand side of Fig. 1) is modeled as a vertical "step" in conductive medium at $x=50$ m, to a height of the maximum tree heights, assumed 18 m, based on the mean tree height of 15 m reported by F. Märcz and the expectation that the tallest trees will dominate the shielding behavior. This elevated step is assumed to extend to infinity in the north–south and west directions, similar to the calculations for the forest edge in Williams et al. (2005). A uniform electric field is imposed on this three-dimensional tree configuration.

The calculated profile of electric field at ground level is shown in Fig. 1 along the x-axis, and is forced to zero at the tree lines to the east and the west, leaving a broad maximum near $X=25$ m. As noted earlier, Märcz and Harrison (2006) report field measurements along the traverse shown in Fig. 1 from 5 m to 30 m. Since the reported measurements are not absolute field, and were not tied in with fixed and calibrated measurements at the locations PG1 and PG2, direct comparisons with the model calculations here are not possible. Their maximum field however was found at $X=25$ m, with a decline for $X>25$ m, in agreement with the model predictions in Fig. 1. Their relative field does not vanish at the edge of the trees however, and this result remains a puzzle. The near-zero value of electric field beneath trees, consistent with their behavior as electrical conductors, was first noted by C.T.R. Wilson (Dee and Wormell, 1965).

According to the model calculations, if all the "trees" in the model are removed, the field at the measurement location PG1 is E_o. If all the trees are allowed to grow up to their final heights, the field at PG1 is still no larger than 61% of its early value. This reduction is within a few percent of the overall decline documented at Nagycenk since 1962 (59%), when according to Märcz and Harrison (2003), the "trees…hardly disturbed the measurements".

It is important to contrast this interpretation with that of Märcz and Harrison (2006). They emphasize the maximum value of electric field recorded at the PG2 location, as evidence that they are beyond the influence of the nearby trees, and hence (by inference) are gaining measurement access to the true ambient fair weather field E_o. But this interpretation ignores the longer-range influence of the extended forest to the west (to the right in Fig. 1), whose superimposed shielding effect leads to a flattening of the field with distance in the intermediate region of the PG1 and PG2 measurement locations in Fig. 1. They are not gaining access to the unshielded field E_o, and if their measurement traverses were extended westward (to the right in Fig. 1 beyond PG2), it is expected that they would not record a flat electric field, but instead a steadily declining field to the edge of the forest at $x=50$ m. The present interpretation of shielding by both sets of trees provides a partial explanation for the small magnitude of the surface electric field at Nagycenk—only 47 V/m in the 2002 time frame—amongst the smallest values recorded at land stations in the literature (Israel, 1973a,b; Table XVII). The generally accepted value of the fair weather field over oceans (Chalmers, 1967; Israel, 1973a,b) is 130 v/m, nearly three times the present measured value at Nagycenk.

Additional issues have been raised in Märcz and Harrison (2006) on the interpretation of the trend in electric field. The method for characterizing the variability of the electric field at Nagycenk by Williams et al. (2005) has been described as "somewhat misleading". The choice in characterizing the variability of the Nagycenk measurements pertains to the physical origin of the variability, and whether it is "local" or "global". The seasonal variation of the electric field at Nagycenk shows a winter maximum and summer minimum (Märcz et al., 1997; Märcz and Harrison, 2003), just opposite to the generally accepted behavior of the global electrical circuit (e.g., Adlerman and Williams, 1996); see also Section 4. In earlier studies, Märcz et al. (1997) agree with Adlerman and Williams (1996) that the seasonal variation of electric field at Nagycenk is aerosol-controlled, and therefore a local rather than global effect. Märcz and Harrison (2003) confirm this interpretation for the seasonal behavior in analyzing their long-term electric field observations. Williams et al. (2005) were therefore reluctant to discard an ill-defined aerosol-controlled annual variance from the overall variance in characterizing the decline in electric field at Nagycenk, a decline that Märcz and Harrison (2005) continue to interpret as a global signal.

10.10. *Harrison (2006, Geophysical Research Letters)*

This author examines the trend in fair weather electric field recorded with 31 sensors at the NASA Kennedy Space Center over the period 1997–2005, to test the hypothesis that the global circuit should increase owing to global warming. Rigorous statistical tests are applied and no statistically significant upward trend is noted.

10.11. *Markson (2007, Bulletin of the American Meteorological Society)*

The high priority quantity ionospheric potential is addressed in Märcz and Harrison (2005), and this deserves discussion in the present context in light of recent developments (Markson, 2007). Ionospheric potential measurements made by Mühleisen and Fischer are shown in Märcz and Harrison (2005) over the interval 1959 to 1971. The same data set had been analyzed earlier by Williams and Renno (1991) for long-term trend, with interest in a global circuit signal from global warming. Both these analyses showed a decline of ionospheric potential with time, affected primarily by the anomalously large values in the early 1960s, with several values exceeding 500 kV (twice the generally accepted mean value of 240 kV). Markson (2007) has revisited these observations and provides strong evidence that the extensive testing of nuclear weapons in the atmosphere (see Section 9) during this period is responsible for this anomaly. It is also plausible that the global effect demonstrated by Markson (2007) is also responsible for the enhanced air-earth current at Kew and its subsequent decline (reported by Harrison and Ingram, (2005) as a local effect) and at Athens (Retalis, 1981 and Märcz and Harrison, 2005), in the same time frame of the heightened nuclear weapons testing.

Markson (2007) goes on to show that when the global data set of ionospheric potential for the period 1954 through 2004 is corrected for the hypothesized effects of weapons testing, and all available measurements of ionospheric potential are considered, that no decrease with time is evident in this quantity over 50 years. This finding is inconsistent with the global interpretation of Märcz and Harrison (2003, 2006) for the declining electric field at Nagycenk, which the calculations shown here reaffirm to be caused primarily by the shielding effects of trees in the vicinity of the sensor.

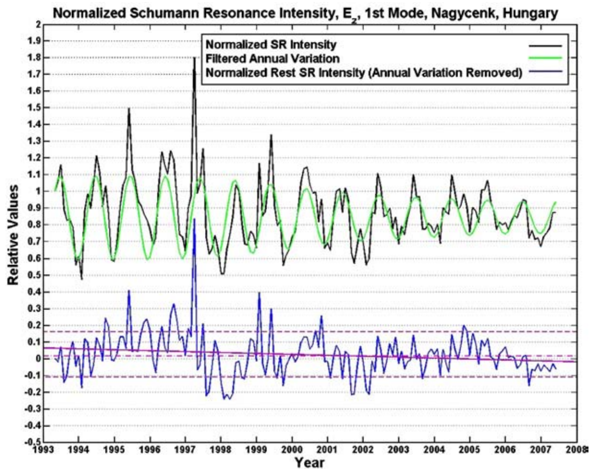

Fig. 2. Schumann resonance intensity recorded at the Nagycenk, Observatory in Hungary for the period 1993–2007 (courtesy of Dr. Gabriella Sátori).

10.12. *Sátori (unpublished)*

The longest continuous record of Schumann resonance intensity, as a measure of the global lightning activity in the AC global circuit, is ongoing at the Nagycenk Observatory in Hungary (Sátori et al., 1999). Fig. 2 shows this 14-year record from 1993 to 2007. Despite the pronounced annual signal, consistent with the discussion in Section 4, no statistically significant long-term trend is apparent over the 14-year interval.

11. Global circuit response to climate change

On balance, the contemporaneous decline of the global circuit, defended on the basis of local measurements of electric field in the presence of interfering effects of aerosol and tree growth, is without strong basis. Absent from this foregoing critical discussion is any mention of global factors expected to cause long-term increases in the global circuit. The most conspicuous factor is the evidence for a contemporaneous increase in the global mean temperature of surface air (Hansen and Lebedeff, 1987; http://data.giss.nasa.gov/gistemp/graphs/). On many time scales, abundant evidence has accumulated that the global circuit should amplify with increasing temperature (Williams, 1992; Price, 1993; Williams, 1999; Sekiguchi et al., 2006; Markson, 2007). The Carnegie curve is the evidence on the diurnal time scale (Price, 1993), as continental zones dominating global circuit source currents are warmed in succession by the zonal motion of the Sun. The semiannual signal in the global circuit (Hogg, 1950; Williams, 1994; Sátori and Zieger, 1996; Füllekrug and Fraser-Smith, 1997) is this evidence on intraseasonal time scales, as the tropics are warmed by the meridional motion of the Sun. The annual signal (Williams, 1994; Nickolaenko et al., 1999; Sátori et al., 1999) is this evidence on the seasonal time scale as NH land is warmed selectively in NH summer asymmetrically with respect to the land-sparse SH. The ENSO (El Nino Southern Oscillation) signal (Williams, 1992; Hamid et al., 2001; Sátori et al., in press) in global lightning activity is the evidence on the interannual time scale, as tropical “chimney” regions undergo temperature variations in response to the east–west oscillation of temperature in the Pacific Ocean.

The global circuit response to temperature change on still longer time scales remains an outstanding question (Williams, 2005; Sátori et al., 2008). The best current evidence is that the global circuit is stable on long time scales, but the quantitative record is quite short, about half a century (Markson, 2007). The convectively adjusted state of the atmosphere (at the level of 1 °C which is important for convective overturn and cloud electrification) is not well specified in a warmer climate. If Convective Available Potential Energy were a climate invariant (Emanuel et al., 1994), this stability could be explained. Since the global circuit is dominated by low latitude current sources, it is appropriate to consider latitudinal trends in global warming (http://data.giss.nasa.gov/gistemp/graphs/).

The current trend in global warming is less by a factor four in the tropics (0.1 °C per decade) than at higher latitudes

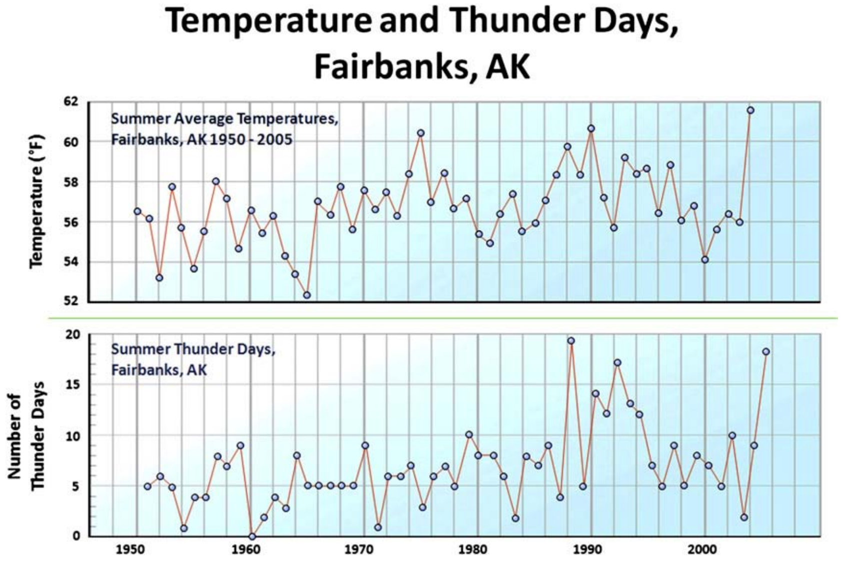

Fig. 3. Variation of a) summertime surface air temperature and b) thunder days (June, July, August, September) for Fairbanks, Alaska.

(0.4 °C per decade), particularly in the NH. This aspect may mute the response of the global circuit to global warming. If the temperature response of ionospheric potential is 10% per °C (Price, 1993; Williams, 1999; Markson, 2007) and the tropics are the dominant control, one might expect a 1% per decade increase in ionospheric potential, Such a small increase may go undetected, given the natural variability of the global circuit on many time scales documented here.

The concentration of global warming at high northern latitudes (Hansen and Lebedeff, 1987 and http://data.giss.nasa.gov/gistemp/graphs/) prompts an examination of secular variations in storm source properties there. Lightning detection networks are often varying with time (addition of sensors, improvements in signal processing, etc) and this can complicate assessments of long-term trends. The thunder day observation is relatively stable by comparison. Fig. 3 shows observations of surface air temperature and thunder day observations in Fairbanks, Alaska (65°N) for the past fifty years. The upward trend in summertime temperature is unmistakable, and amounts to a total increase of 2 °C in 80 years. A plausible upward trend in thunder days is also apparent.

12. Global circuit impact on climate?

The previous section addressed some of the evidence that tropospheric weather (short time scales) and climate (long time scales) influence the global electrical circuit. In contrast, Tinsley et al. (2007a,b) and Harrison (2004a,b) investigate if the global circuit can influence climate. The proposed microphysical mechanisms, still in need of quantitative evaluation, involve effects of cloud droplet charge on precipitation efficiency, ion-assisted formation of ultrafine aerosol, electro-scavenging of ice forming nuclei, and increase in ice nucleation capability of charged aerosols. The macrophysical responses, predicted in many cases to depend on the air-earth current Jz (Tinsley et al., 2007a,b), are difficult to evaluate because an acknowledged major cause for the latter quantity, over a large portion of the global circuit, is weather and climate. Tests are needed that unambiguously distinguish cause and effect here.

13. Conclusions

Substantial progress has been achieved in understanding the global electrical circuit, and yet controversial issues remain. Renewed efforts are needed to monitor the global circuit on a continuous basis toward exploiting this natural framework for the study of global change.

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