XV International Conference on Atmospheric Electricity, 15-20 June 2014, Norman, Oklahoma, U.S.A.

Global Circuit Response to the 11-Year Solar Cycle: Changes in Source or in Medium?

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ABSTRACT: Modifications to both the DC and AC global circuits are considered on both short time scales and on the 11-year solar cycle time scale. New long-term records of Schumann resonances are considered as documentation of the AC global circuit. In most cases, changes in the medium of the global circuit provide a better qualitative explanation than intrinsic source changes (i.e., lightning and electrified clouds) for the variations in the global circuit. Further work is needed with the quantitative details.

INTRODUCTION

This study is concerned with the behavior of the global electrical circuit on the long time scale of the 11-year solar cycle. Here we are considering both the conventional DC global circuit whose source is worldwide electrified weather, and the AC global circuit (Schumann resonances) whose source is worldwide lightning. Normally one considers the global circuit as a time-invariant medium in which lightning and electrified weather sources serve alone to control its global response. That is to say that if the worldwide electrified weather doubles, the ionospheric potential is expected to double, and if the global lightning activity doubled, the measured Schumann resonance intensity should double everywhere. In this study, attention is focused on how natural changes in the global circuit medium can cause changes in global circuit response that can masquerade as changes in the source.

Historically speaking, the DC and AC (Schumann resonances) global circuits have been treated separately and independently. In this study, these two aspects are examined together because of the perceived parallelism in the importance of medium changes. Accordingly, a substantial portion of this study is in the nature of a review paper, in the interest of drawing together this parallel behavior between DC and AC global circuits.

Many ideas have been advanced for how the solar cycle might influence the source for the global circuit, beginning with Ney (1959) and Dickinson (1975), and this general area of research has taken on the name ‘Sun-weather problem’ (Gray, 2010). Early skepticism about a direct solar cycle impact on atmospheric thermodynamics remains today—the variation of the output from the Sun is only 0.1% over the 11 year solar cycle. More recent skepticism about a prominent role from cloud microphysics modulated by modulation of galactic cosmic radiation has come from a study over the solar cycle (Kulmala et al., 2010). Furthermore, no solar cycle signal in the global lightning observed from space (Christian et al., 2003) has been identified.

For these several reasons, we chose here to concentrate only on possible variations in the medium to explain changes in global response. Energetic particle fluxes often penetrate deeply enough to influence the global circuit medium but with the exception of the cosmic radiation, not sufficiently far to be able to influence the thunderstorms and the lightning they contain. A possible increase in lightning initiation by enhanced cosmic radiation will not enable an increase in lightning energy, and may in fact reduce it. The influence of cosmic radiation on lightning remains to be firmly established. No evidence has surfaced that the strongly established ice-ice non-inductive mechanism for thunderstorm electrification is influenced by cosmic radiation.

All of these aspects serve as motivation to focus on the possible role of medium changes in global circuit behavior. In the following sections, both previously published and new evidence is presented for this role, on both short and long time scales.

THE DC GLOBAL CIRCUIT

Short time scales

Modifications of the DC global circuit on short time scales (~hours) have been documented in energetic solar proton events. Mühleisen and Reiter (1973) made comparisons between ionospheric potential and electric field and current measurements and showed positive correlations with a satellite-recorded solar proton event in the energy range 5-21 MeV. An increase in ionosphere potential of about 25% was shown during that event.

Markson (1975) first suggested that a modification of the electrical conductivity over thunderstorms by cosmic radiation could enhance the Wilson conduction current to the ionosphere without appreciable modification of the fair-weather return portion of the global circuit, and thereby enhance the ionospheric potential Vi. Markson (1978) estimated that a change in Vi of 40 % could be enacted by a 50% change in conductivity over the thunderstorm. In the latter study, it was stated that “solar modulation of the Earth’s electric field can be explained without changing the thunderstorm generator itself”. Willett (1979) modelled the effect of the proposed medium change with a Holzer-Saxon (1952) treatment of the global circuit, and found a notably smaller response of Vi to the conductivity perturbation, but the sign of the change was in agreement.

Following up on the notion that changes in upper atmosphere conductivity could modulate the global circuit (Markson, 1975; 1978), the role of variable cosmic radiation was explored (Markson, 1981). Positive correlations between ionospheric potential and cosmic ray flux were found, with 10% changes in cosmic rays associated with 10-20% changes in Vi. The physical interpretation of these findings was aimed primarily at the medium of the global circuit, but some allowance was made for possible effects on the thunderstorm source. The 'Chapman layer' height for galactic cosmic rays, the so-called Pfotzer maximum, is in the range of 20 km altitude for mid-latitude conditions.

More recently, positive correlations have been found between the nuclear bomb testing in the atmosphere and the record of ionospheric potential (Markson, 2007). The time scale here is shorter than the 11 year solar cycle time scale but not so short as to prevent possible aliasing of the longer time scale phenomenon, as will be discussed. The physical interpretation for the effect of the bomb testing on the global circuit is based on the residue of radioactivity in the stratosphere that serves to enhance the conductivity over thunderstorms, increase the Wilson conduction current, and enhance the Vi voltage drop in the fair weather portion of the global circuit.

Long time scale (11 year solar cycle)

The behavior of the DC global circuit on the 11 year solar cycle time scale was examined by Fischer and Mühleisen (1972) (see also Reiter, 1992) with their data set of ionospheric potential during the period 1959-1974. Vi was found to be 25% larger during solar minimum in comparison with solar maximum. Since the flux of galactic cosmic rays is well known to be larger at solar minimum than maximum (by some 10-15 %), this earlier finding of Fischer and Mühleisen (1972) is consistent with the later findings of Markson (1981) on inferred cosmic ray effects.

The response of the DC global circuit to the 11 year solar cycle was also investigated by Olson (1977; 1983) by measurements of the air-earth current over the period 1966-1982. Consistent with the Vi measurements, a larger air-earth current was found at solar minimum than at solar maximum, when the modifying influence of the galactic cosmic radiation is also maximum. More recently Harrison and Usoskin (2010) have found evidence in air-earth current records at Lerwick Observatory in the UK that are consistent with Olson's measurements over the solar cycle.

THE AC GLOBAL CIRCUIT (SCHUMANN RESONANCES)

The existence of quasi-standing global waves (‘Schumann resonances’) in the same thin insulating atmospheric layer that supports the DC global circuit has led to the name “AC global circuit” for this phenomenon. In recent years, the organization of various Schumann resonance data sets has been undertaken, and are shown in Figure 1. An additional record at Arrival Heights, Antarctica (77.8S; 166.7W) (Bezrodny et al., 2007) has also been assembled (Füllekrug, 1995; Füllekrug et al., 2002; Füllekrug, personal communication, 2002). These records enable an investigation of the possible effects of a change in the ionospheric medium on the measured Schumann resonance intensities, and their distinction from variations in the lightning source. The most conspicuous feature of all the records shown in Figure 1 is the consistent annual cycle, with maximum in Northern Hemisphere summer. This part of the record is unambiguously linked with the global annual variation of lightning activity that has also been established on the basis of optical measurements from satellite (Christian et al., 2003) and from a global network of VLF receivers (Virts et al., 2013). Other aspects of the three multi-station records in Figure 1 are quite different and require appeal to changes in medium to understand.

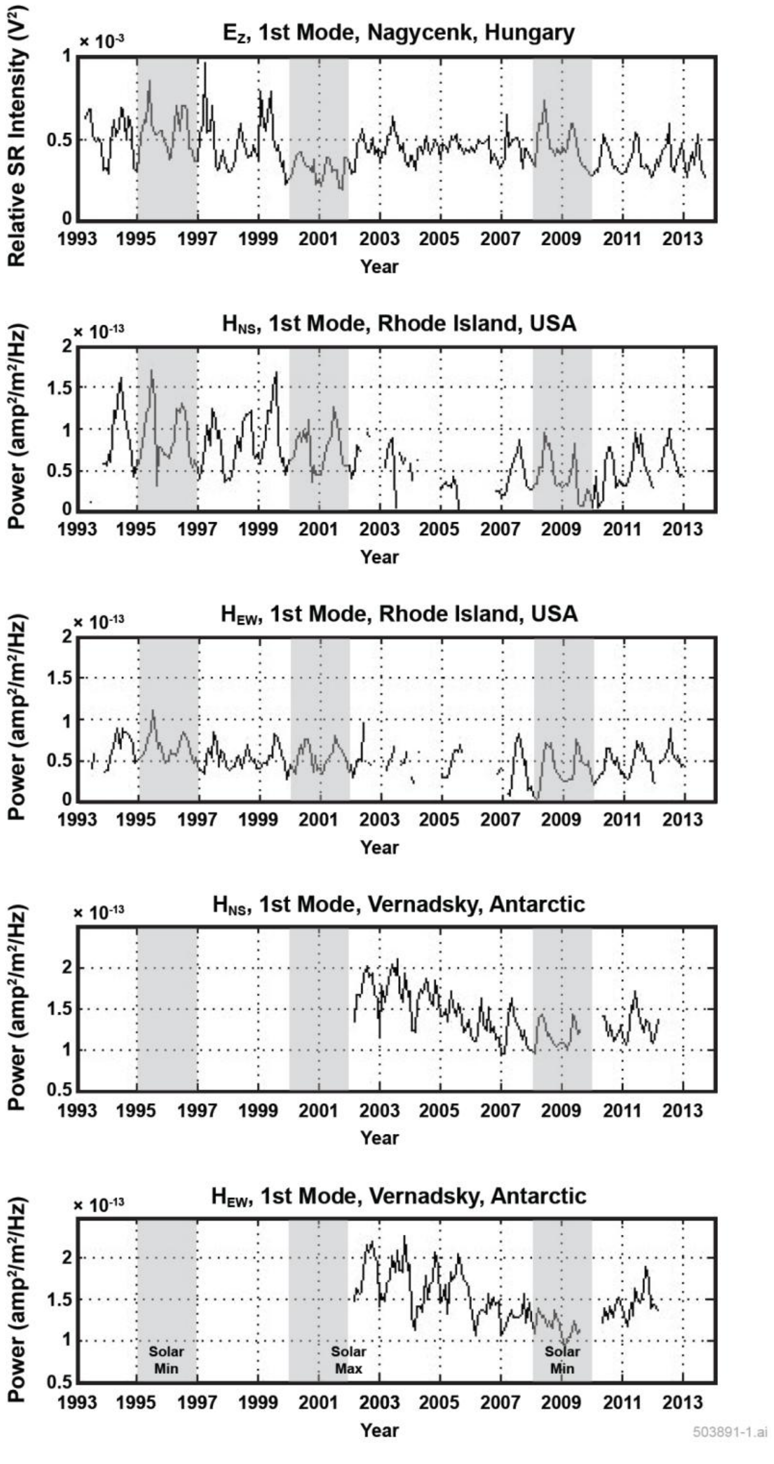

Figure 1. Long-term records of Schumann resonance intensity for (top) Nagycenk, Hungary in vertical electric field, (middle) West Greenwich, RI, USA, two horizontal components of magnetic field, and (bottom) Vernadsky, Antarctica, two horizontal components of magnetic field.

Both the modelling and the theoretical interpretation of Schumann resonances have been greatly aided by evidence for control by two characteristic ionospheric heights. These two heights were first identified by Madden and Thompson (1965) in a modelling treatment that incorporated aeronomical observations. The two heights were identified as maxima in ionospheric dissipation of EM wave energy. In later theoretical work in cylindrical geometry, two heights were identified on the basis of an analytical treatment (Greifinger and Greifinger, 1978; 1979), and soon thereafter this theory found application in the spherical geometry of Schumann resonances (Sentman, 1990; Mushtak and Williams, 2002; Greifinger et al., 2007). In the transmission line network analogy pioneered by Madden and Thompson (1965) and nurtured by Kirillov and colleagues (Kirillov, 1996; Kirillov et al., 1997), the two characteristic heights find representations in distinct impedance elements in the equivalent spherical circuit. The lower height is represented by a capacitor and denoted H_C and the upper height represented by an inductor and denoted H_L. Satori et al. (2005) have already produced evidence that the changes in this upper height can be affected by solar X-radiation over the 11-year solar cycle, as will be discussed further below.

The transmission line treatment of a non-uniform Earth-ionosphere cavity is particularly valuable in understanding the effects of height changes on local changes in electric and magnetic fields (Greifinger et al., 2005). The key symbolic equations from that study are replicated below:

$$E_r(f;S\to O)\sim M_S(f)\frac{\tilde{H}_L(S)}{\tilde{H}_C(S)}\frac{1}{\tilde{H}_C(O)}\left[U(S\to O)\right], \tag{1}$$

$$H_\varphi(f;S\to O)\sim M_S(f)\frac{\tilde{H}_L(S)}{\tilde{H}_C(S)}\left[\frac{1}{\tilde{H}_L(O)}\frac{\partial U(S\to O)}{\partial\theta}\right] \tag{2}$$

$$H_\theta(f;S\to O)\sim M_S(f)\frac{\tilde{H}_L(S)}{\tilde{H}_C(S)}\frac{1}{\tilde{H}_L(O)}\frac{\partial\tilde{U}(S\to O)}{\partial\varphi}, \tag{3}$$

Following these predictions, the fields are influenced by the heights of the cavity at the source ($H_C(S)$ and $H_L(S)$), and by the heights at the observer location ($H_C(O)$ and $H_L(O)$).

Short time scales

Solar proton events affect both the DC and AC global circuits, and good evidence for synchronous amplitude increases (of the order of a few tens of %) at the high latitude site in Antarctica known as Arrival Heights can be found in Schlegel and Füllekrug (1999). These authors made use of Sentman and Fraser's (1991) ionospheric height correction for SR intensity, applicable to the global waveguide, and found that the predictions (<10%) fell substantially short of the observations. Schlegel and Füllekrug did not invoke any change in the lightning source to improve the agreement with their observations. If we instead make use of equations (2) and (3), and assume the relevant height changes are confined to the polar region where the solar protons are unshielded by the poloidal magnetic field, then only the local $H_L(O)$ height parameter is affected. (We are assuming no change in waveguide height in the vicinity of the main tropical sources, as this low latitude region is shielded by the magnetic field from the effects of solar proton events.) Using the 12 km reduction in height caused by the solar proton event documented in Schlegel and Füllekrug (1999), we arrive at an intensity change of 38%, in much better agreement with the observations.

A strong solar proton event at a station at high northern latitude (Lovozero observatory (68 N, 35 E)) has also been shown to cause a large amplitude increase in the lower Schumann resonance band (0.1-20 Hz) (Roldugin et al., 2003), consistent with the larger collection of events in Antarctica (Schlegel and Fullekrug, 1999).

The Vernadsky records in Figure 1 have not been carefully examined for solar proton events, but in the context of short time scales, it is readily apparent that this record is exhibiting substantially greater short time scale variance in comparison with the station data for Nagycenk and Rhode Island at mid-latitude. This finding is likely related to the more highly variable nature of the ionosphere in the polar region than at mid-latitude, but this speculation will be pursued further in future work by station inter-comparisons: Vernadsky with Arrival Heights, and the polar stations with the mid-latitude stations on these shorter time scales.

Long time scale (11 year solar cycle)

By good fortune, the Vernadsky records in Figure 1 for Antarctica have a duration sufficient to explore the effects of the 11-year solar cycle. The conspicuous feature of both magnetic records for Vernadsky is the steady decline from the solar maximum of 2001 to the solar minimum near 2009, with an overall change in intensity of order 50%. In seeking an explanation for this long-term variation, it is necessary to consider findings in a number of earlier studies.

Satori et al. (2005) had earlier shown the importance of the solar X-radiation at solar maximum in modifying the upper D region conductivity and the upper characteristic height (Figure 2). This medium modification was shown to increase all the modal frequencies and all the modal Q-factors. Kulak et al. (2003) have reported similar effects. The intensity changes were not focused on in these earlier studies

For a station in the polar region, the solar X-radiation is not expected to have major influence on the ionization profile because the X-rays are highly obliquely incidence. As shown schematically in Figure 2, the influential particles in the polar regions are those energetic charged particles that can follow the magnetic field lines. The two major charged particles are protons and electrons. The solar protons have already been discussed in the context of the energetic solar proton events on short time scales, but this contribution is too intermittent to account for a persistent modification of the ionospheric height on the solar cycle time scale. The electrons that enter polar regions from the magnetosphere along the magnetic field are the main players in a quantity called “auroral power” (Emery et al., 2008). The polar power has been shown to have “in-phase” behavior with the 11 year solar cycle (Zheng et al., 2013), with a variation of nearly a factor of two on that time scale. Earlier studies had shown that electrons with energy in the 40-50 keV range can have an appreciable impact on the ionization and hence the profile of electrical conductivity in the polar regions (Whitten and Poppoff, 1965) in a range of height important for Schumann resonances. Unfortunately this range of electron energy is slightly higher than the limit that has been considered in the calculation of auroral power (Emery et al., 2008). For purposes of comparison with auroral power, the power associated with galactic cosmic radiation (Friedlander, 2000) into the same polar zone considered for auroral power is less than 1% of the latter quantity, although the energies involved with the cosmic radiation allow ionization to reach lower altitudes. The problem with cosmic radiation as an explanation here is that this quantity is minimum at solar max.

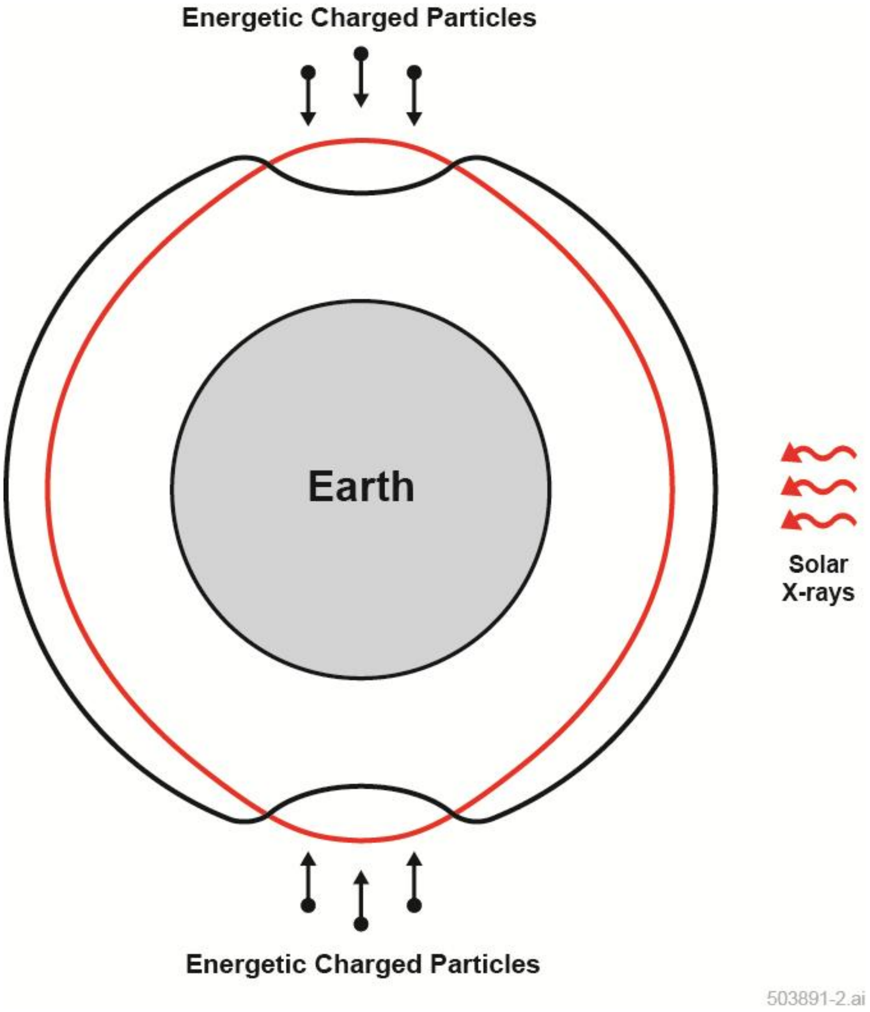

Figure 2. Schematic modification of the upper characteristic height of the ionosphere by solar X-radiation (red line) and by energetic charged particles (black line) in the two polar regions. These height changes represent the principal medium changes that affect the SR intensity on the solar cycle time scale.

Füllekrug et al. (2002) looked at ionospheric height variations at Arrival Heights for the period 1988-2000 using a theoretical model, and found a 4% variation in the upper characteristic height over the 11 year solar cycle, with a maximum height at solar minimum. This finding is qualitatively consistent with both the data record at Arrival Heights and Vernadsky. The use of that estimate in the height correction equations (1) to (3) discussed earlier, yields an 8% change in the magnetic intensity for Arrival Heights, to be compared with a 30% change in the actual record (not shown). This suggests that the actual height change at Arrival Heights was substantially greater, consistent with the analysis of the solar proton events on short time scales discussed earlier. Quantitatively speaking, the 4% height change inferred by Füllekrug et al. (2002) was close to the height change at mid-latitude stations needed to account for the observed changes in modal frequency and Q-factor in Satori et al. (2005). But the comparisons discussed here suggest that the change in the ionospheric height on the long time scale is substantially greater in the polar regions than at mid-latitude, as illustrated schematically in Figure 2.

The interpretation of the intensity records in Figure 1 at the mid-latitude stations is more problematic. At the outset, despite the global reach of Schumann resonances, one cannot expect two records of intensity at distant locations to track together because source-receiver distances do matter (in addition to the height effects embodied in equations (1) to (3)) and they are inevitably not matched from station to station. Furthermore, in the case of Nagycenk and Rhode Island, two different fields are being considered, and the distance dependence on intensity is distinctly different for electric and magnetic field. But considering the Nagycenk record initially, one can discern an anti-phase relationship between intensity and the 11-year solar cycle, with tendency for larger intensity at solar minima (1996 and 2009) and minimum intensity at solar max (2001). This behavior can be compared with the tendency for the DC global circuit to be anti-phase with the solar cycle (Fischer and Mühleisen, 1972; Olson, 1983) and with the anti-phase behavior of the thunder day behavior in Brazil documented in Pinto et al. (2013), suggesting that long term variations in the global lightning source might be involved. However, the predictions for the effect of possible medium change (equations (1)) for the electric field also deserve careful consideration. Following again the evidence in Satori et al. (2005), the upper characteristic height H_L should descend at solar maximum (see Figure 2), leading to a reduction in electric field intensity at solar maximum, also qualitatively consistent with the observations in Figure 1 in the vicinity of 2001. The opposite phase behavior in intensity at Nagycenk on the one hand, and at Vernadsky (and Arrival Heights, not shown) over the solar cycle is strong evidence that variations in the global source are not responsible for the intensity variations in Schumann resonances.

The interpretation of the Rhode Island magnetic records over the solar cycle presents the greatest difficulty. Boldi et al. (2014) have also analyzed this record in comparison with other solar cycle indices, and do not find substantial correlation on the 11-year time scale. (Strong correlation with SR modal frequency and Q-factor is found, however, consistent with the earlier work by Satori et al. (2005). The initial decline from the initial solar minimum period of 1996 to solar max in 2002 is apparent, and that finds qualitative explanation with the expected lowering of H_L but neither the Hew nor the Hns intensity is restored to a higher level as the next solar minimum (2009) is approached. Some possible problems with equipment in the data gap of 2006 may be important and that is still being examined. One additional problem in the present context is the null result on SR intensity variation when the ionosphere is subjected to short term variations of X-radiation of the same intensity documented over the 11-year solar cycle. It is interesting to note that the period (2002-2012) over which the record from the NASA TRMM Lightning Imaging Sensor and the global temperature record are statistically flat (Williams, 2012) is also a period of steadiness in intensity for both the Rhode Island and Nagycenk records.

DISCUSSION

The literature of atmospheric electricity documents a long history of search for a solar cycle signal in the global lighting source. The classical reference on that search in the realm of thunder day observations is that of Brooks (1934). The figure in that paper showing the 11-year variation for a few stations conveys the result that thunder days will vary in phase with the solar cycle, but in fact none of the raw data records analyzed are shown, and the actual correlation coefficients in the sunspot comparisons are quite small, not to mention the finding of a highly variable phase. Kleymenova (1967) also analyzed thunder days for a large number of stations, but also did not show either raw data records or a consistent phase relationship in the analysis. Fischer and Mühlheisen (1972) looked also with thunder day data from many stations, but did not find any consistent relationship on the long time scale. Perhaps the most convincing evidence for an 11-year signal in thunder day records is found in the recent work of Pinto et al. (2013). A consistent anti-phase relationship with the solar cycle was found (consistent with the variation of the DC global circuit documented in an earlier section, but this was only for a small number of meteorological stations in southern Brazil.

To examine the possibility that rainfall in the Amazon basin in South America was following the solar cycle, the century-long gage measurement of discharge in Manaus harbor, at the confluence of the Rio Negro and Solimoes Rivers, was examined. No solar cycle was found. A similar procedure for the century-long Congo River discharge in Africa also produced no positive result (Williams, 2012).

Turning now from thunder day data to optical detection of global lighting from space (Christian et al. 2003), recent analysis shows no evidence for the 11 year solar cycle in this data record (H. Christian and D. Buechler, personal communication, 2013; see also Williams, 2012)

The intensity records at Vernadsky, Arrival Heights (not shown) and Nagycenk show behaviors over the 11-year solar cycle that find qualitative explanation in the modifications in the Schumann cavity that are to be expected from extraterrestrial forcing that has been documented elsewhere. The interpretation of the complete records in Rhode Island is more problematic, as a correlation with the solar cycle is less apparent.

The anti-phase relationship over the solar cycle found earlier in ionospheric potential observations for the DC global circuit by Fischer and Mühleisen (1972) may have been contaminated by the effects of nuclear testing identified recently by Markson (2007) and this issue deserves revisitation. The independent evidence for anti-phase behavior in Olson (1983) and Usoskin and Harrison (2010) in air-earth current observations may also have been influenced by radioactive material in the stratosphere during intensified bomb tests in the 1960s.

CONCLUSION

A consideration of the observations and theory for the behavior of both the DC and AC global circuits suggests that the change in global circuit medium is predominating over variation in source over the time scale of the 11 year solar cycle. Quantitative discrepancies remain and are deserving of further study.

ACKNOWLEDGEMENTS

The provision of a Fulbright Post-doctoral fellowship to one author (Anirban Guha) enabled the organization of the Rhode Island SR record. The sustained measurement of SR in West Greenwich, RI has been possible through the generous of assistance of Thomas Mitchell and colleagues at the Alton Jones Campus of the University of Rhode Island.

The authors are thankful to the National Antarctic Scientific Center of Ukraine, State Agency on Science, Innovation and Informatization of Ukraine for providing the ELF data recorded at the Ukrainian Antarctic Station “Academic Vernadsky”.

Discussions with Ralph Markson on the DC global circuit, with Martin Füllekrug concerning the SR amplitude record at Arrival Heights, Antarctica and with Barbara Emery on auroral power are much appreciated.

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