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Recent progress on the global electrical circuit

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ABSTRACT

Research work on the global electrical circuit (GEC) is reviewed, with an emphasis on the period since the last International Conference on Atmospheric Electricity (ICAE) in Beijing, China in 2007. This review was presented initially (in more abbreviated form) at the ICAE in Rio de Janeiro, Brazil in August 2011. The topics selected for discussion in the context of the GEC are electrified shower clouds (Section 2), mesoscale convective systems (Section 3), measurement of the DC electric field (Section 4), electrical quantities and energy (Section 5), convective turbulent currents (Section 6), lightning (Section 7), the Earth–ionosphere waveguide (Section 8), variations on the ENSO time scale (Section 9), model simulations of short-term variability and long-term trend of the GEC (Section 10), the weekly cycle in aerosol and lightning (Section 11), conductivity perturbations and the effects of enhanced radioactivity (Section 12), cosmic ray-mediated cloud microphysics on the 11-year solar cycle (Section 13), the impact of a gamma ray flare (Section 14), and planetary electrification (Section 15).

Contents

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1. Introduction

This paper is concerned with a critical review of work on the global electrical circuit (GEC) that has taken place since the time of the last International Conference on Atmospheric Electricity in 2007 in Beijing, China. The review is composed of an elaboration of subtopics selected for presentation and discussion at the most recent ICAE in Rio de Janeiro in August 2011. The topics selected for discussion are illustrated in Fig. 1, showing the DC global circuit on the left and the AC global circuit (Schumann resonances) on the right. The structure for both global circuits is afforded by the thin insulating layer of atmosphere (whose thickness is much exaggerated in Fig. 1) sandwiched between the conductive Earth and the conductive ionosphere. The giant leaky capacitor on the left supports the voltage Vi (so called ionospheric potential equal to about 240 kV) between the conductive Earth and the lower ionosphere. The giant spherical electromagnetic waveguide on the right supports resonant waves excited by lightning whose wavelengths are dictated by the circumference of the Earth and the speed of light. The topics illustrated and discussed are electrified shower clouds (Section 2), mesoscale convective systems (Section 3), measurement of the DC electric field (Section 4), electrical quantities and energy (Section 5), convective turbulent currents (Section 6), lightning (Section 7), the Earth-ionosphere waveguide (Section 8), variations on the ENSO time scale (Section 9), model simulations of the short-term variability and the long-term trend of the GEC (Section 10), the weekly cycle in aerosol and lightning (Section 11), conductivity perturbations and the effects of enhanced radioactivity (Section 12), cosmic ray-mediated cloud microphysics on the 11-year solar cycle (Section 13), the impact of a gamma ray flare (Section 14), and planetary electrification (Section 15). For other recent discussion on the GEC that may range beyond these subtopics, the reader may wish to consult the articles by Markson (2007); Anisimov and Mareev (2008); Aplin et al. (2008); Rycroft et al. (2008); Tinsley (2008); Williams (2009); Mareev (2010); Siingh et al. (2011); Rycroft and Harrison (2012), and Rycroft et al. (2012).

Renewed interest in the GEC problems arose during the last decade, in particular due to climate applications. We have chosen topics to review where either significant progress has been achieved recently (like the role of electrified shower clouds, ENSO climate variations, new experimental results on global and regional lightning detection, new models for the DC GEC), or other topics (like the possible weekly cycle in the GEC, the impact of a galactic gamma ray flare, and planetary electrification) where provocative results have been obtained, but where new extensive research is needed. Special attention has been given to the physical mechanisms of the GEC addressed in theoretical modeling, and the experimental efforts to measure the two global circuits shown in Fig. 1.

2. Electrified shower clouds and their role in the GEC

The 'Carnegie curve' of atmospheric electricity (Chalmers, 1967; Israel, 1973; Harrison, 2013) is widely recognized as the climatological diurnal variation of the DC GEC (Markson, 2007; Williams, 2009). This variation is generally in good agreement with the diurnal variation of ionospheric potential Vi which is the preferred measure of the GEC (Markson, 2007). The 'global circuit hypothesis' (Wilson, 1920) claims that these characteristic diurnal variations are maintained by variations in electrified moist convection worldwide. It should be noted that for a long time the convective clouds exhibiting lightning activity were mostly implied when discussing the origins of diurnal variation of the DC GEC. Problems with matching the diurnal amplitude variation of the Carnegie curve with global land-based thunder day observations led Whipple (1929) to postulate the existence of a diurnally-flat distribution of oceanic thunderstorms. It seems to have been forgotten at the time that C.T.R. Wilson had earlier suggested (Wilson, 1920) an important role for electrified shower clouds (ESCs), in addition to thunderstorms, in maintaining the global supply current. The existence of ESCs, with an electrical polarity appropriate for contributing to the potential difference between Earth and atmosphere, has recently been verified in aircraft overflights of cumulonimbus clouds by NASA Marshall Space Flight Center (Mach et al., 2009, 2010, 2011).

Motivated by the valuable new information on ESCs in the latter investigations, two studies have recently appeared (Liu et al., 2010; Mach et al., 2011) that independently assess the role of these non-thunderstorm clouds in the diurnal variation of the GEC. Both studies are limited by the assumptions necessary in making their respective assessments.

The first of these efforts builds directly on the database of ESCs in the aircraft overflight measurements (Mach et al., 2011). Curiously, the mean upward Wilson current from the cloud tops for all storms over ocean (1.7 A) substantially exceeds that for storms over land (0.95 A). When it is further assumed that the relative numbers of thunderstorms and ESCs is the same globally as in the overflight data, the diurnal variation of current from all categories (ESCs and thunderstorms for land and ocean) is computed. The land population of ESCs is lower than the land population of thunderstorms by a factor of ~3 and the oceanic population of ESCs is approximately flat over the diurnal cycle. The total charging current for the ESCs was estimated to be only ~10% of that provided by thunderstorms.

The second assessment (Liu et al., 2010) made use of TRMM satellite observations (the Lightning Imaging Sensor (LIS) and the Precipitation Radar) to estimate the global population of ESCs. The vertical development of the mixed phase region on radar was assumed to represent the graupel particles responsible for electrification of shower clouds, also showing no lightning flashes with the LIS. The quantitative rules for ESCs pertained to the in situ temperature T of the 30 dBZ radar reflectivity level, based on numerous ground-based studies:

$$T\ (30\ \text{dBZ}) < -10\ ^\circ\text{C} \quad \text{over land}$$

$$T\ (30\ \text{dBZ}) < -17\ ^\circ\text{C} \quad \text{over ocean}$$

With these rules, it was estimated that the number of ESCs exceeded the number of thunderclouds by a factor of three, with a maximum population in the Maritime Continent and a minimum population in Africa. Assuming that the Wilson current for an individual electrified shower cloud is 25% of that for a thunderstorm, the total charging current to the GEC from ESCs was found to be of the same order as that from thunderstorms, in agreement with Wilson's (1920) initial speculation.