A.C./D.C. Atmospheric Global Electric Circuit Phenomena

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***Abstract*—We review the global circuit driven by thunderstorms and electrified rain clouds. With the ionosphere at an equipotential of ~ +250kV with respect to the Earth, the load in the circuit is the fair weather atmosphere; its conductivity is mainly determined by the flux of galactic cosmic rays. The circuit exhibits variability in both space and time by more than fifteen orders of magnitude. We discuss results produced by a new electrical engineering analogue model of the circuit constructed using the *PSpice* software package. Finally, we consider several interesting new experimental observations relating to the topic.**

Keywords-analogue model, atmospheric conductivity profile, global circuit, ionosphere, key results, thunderstorms,variability

I. INTRODUCTION

The D.C. aspects of the topic of this overview paper were pioneered in the 1920s by Wilson [1]. He proposed that thunderstorms and electrified shower (rain) clouds drive currents totaling ~ 1kA up through the atmosphere into the ionosphere, raising its potential to ~ +250kV with respect to the Earth's potential. The circuit is completed through the fair weather atmosphere remote from thunderstorms, where the current density is ~ 2pA/m^2, and through the good conducting land and sea surfaces. The atmosphere is an imperfect conductor, with ionization being generated over the land surface by radon escaping from the ground, and in the atmosphere by incoming galactic cosmic rays of different energies. During the 1990s and the 2000s significant progress was made in the subject; this has been reviewed by Harrison [2], Aplin et al. [3], Rycroft et al. [4], and Williams [5].

Rycroft et al. [6], Neubert et al. [7] and Rycroft and Odzimek [8] described a new electrical engineering model of the global circuit created using the *PSpice* software package. The crucial feature of this model is the variation of the atmospheric electrical conductivity with height, from ~10^{-14}S/m at the Earth's surface to ~ 10^{-7}S/m at the bottom of the ionosphere at 80km altitude. Rycroft et al. [6] found that the two generators each contribute similar values of current (~ 0.5kA each) to the circuit. They also found that, overall, cloud-to-ground lightning discharges, often having peak return stroke currents in excess of 50kA, contribute little to maintaining the high ionospheric potential. Rycroft and Odzimek [8] modeled the mesospheric electric discharges known as column sprites and carrot sprites, which may occur above an active thunderstorm ~ 1ms after a large positive cloud-to-ground lightning flash - see Fullekrug et al. [9]. They showed a sprite alters the ionospheric potential by only ~ 1V.

II. SOME NEW THOUGHTS ON THE GLOBAL CIRCUIT

A principal feature of the global circuit is the enormous range of spatial scales that is inherent in the many phenomena being considered. These aspects are illustrated as a function of altitude in Fig. 1, where words in black indicate physical features and words in blue indicate regions where interesting physical phenomena occur. Here CCNs refer to cloud condensation nuclei, SC to stratocumulus clouds, TCs to thunderstorm cells, MCS to a mesoscale convective system (a large thunderstorm nearing the end of its life), and TLEs to transient luminous events such as sprites and elves.

Almost as large as the range of spatial scales is the range of temporal scales involved. Fig. 2 shows this; words in black show important physical effects whereas words in blue indicate physical processes. Here ICs refer to intra-cloud lightning discharges, such as from the – charge at the bottom of a thundercloud to the + charge at the top. These may well be what initiate the fascinating and recently observed Terrestrial Gamma-ray Flashes (TGFs) [10]. The boundary between D.C. and A.C. phenomena is put at ~ 200s, the *RC* time constant of the global circuit. It is worth noting that half of the atmospheric columnar resistance *R* occurs at altitudes less than 2km.

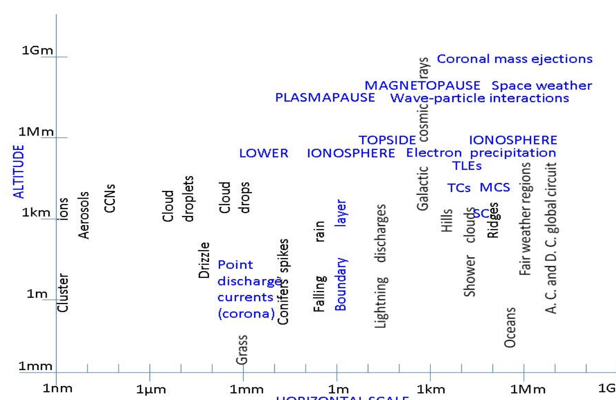

Figure 1. Diagram indicating the huge range of spatial scales involved.

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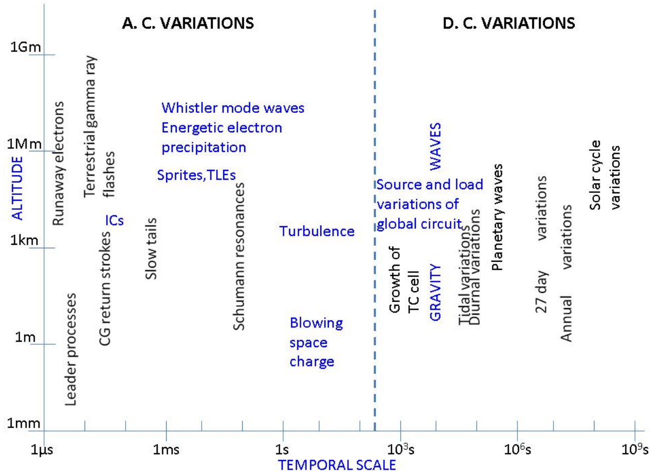

Figure 2. Diagram showing the wide range of temporal scales involved.

The range of A.C. (electromagnetic wave) phenomena involved is indicated in more detail in Fig. 3. Starting at the lowest frequencies, these are, for example, Alfven waves propagating through the magnetosphere, Schumann resonances of the global Earth-ionosphere cavity, and atmospherics (sferics, for short) radiated by lightning discharges propagating in the Earth-ionosphere waveguide over Mm. Whistlers are ducted through the magnetosphere, and whistler mode waves such as chorus and hiss arise from plasma instabilities in the magnetosphere; a theoretical monograph on the generation of these has been published by Trakhtengerts and Rycroft [11].

Using simultaneous days of Weissenau-launched balloon electric field data and Kew Observatory atmospheric electricity data taken between 1966 and 1971, Harrison and Bennett [12] showed that the ionospheric potential divided by the surface potential gradient is linearly related to the derived air conductivity at Kew. This result clearly indicates that the global circuit concept holds over the whole of Europe.

A.C. Sources:
Magnetospheric sources, geomagnetic pulsations at **ULF (< 3 Hz)**

Lightning discharges, both – and + CG (cloud-to ground), and IC (intra-cloud), and also sprites, radiate:
at ELF (3 Hz to 3 kHz)
(a) ionospheric Alfven resonator, at ~ few Hz
(b) Schumann resonances, at 8, 14, 20, 26 ..... Hz, around the world
(c) slow tails, and sprites, at a few 100 Hz
(d) sferics, propagation in the Earth-ionosphere waveguide
(waveguide cut off ~ 1.7 kHz, at night)
at ELF and VLF (3 kHz to 30 kHz)
(a) sferics propagating in Earth-ionosphere waveguide
(b) whistlers
Also emissions due to magnetospheric plasma instabilities, such as chorus and hiss, propagating in the whistler mode (see Trakhtengerts and Rycroft, Whistler and Alfven mode cyclotron masers in space (2008) CUP, 354 pages)
at LF (30 to 300 kHz)
(a) sferics
(b) broadband hiss (possibly associated with TGFs)

Figure 3. A.C. global circuit sources.

Harrison and Usoskin [13] showed that monthly average estimates of the ionospheric potential are linearly related to the Climax (Colorado) neutron monitor rate, which indicates the flux of galactic cosmic rays of > 3GeV. At solar maximum, when the galactic cosmic ray flux is reduced (due to enhanced scattering away from the Earth by more irregular interplanetary magnetic fields), the atmospheric electrical conductivity is less, and so is the ionospheric potential. This mechanism therefore directly links solar activity to the stratosphere and troposphere via the global atmospheric electric circuit.

Nicoll [14] has described a cloud edge charge detector carried up by a meteorological balloon. At the bottom of a low level cloud, an instrumented aircraft detected cloud droplets. From the balloon data, in a region where the conduction current density is ~ $2pA/m^2$, and descending through this same cloud the air conductivity was calculated; it was found to be three times less than outside the cloud. Nicoll and Harrison [15] used Gauss' law to show that the negative space charge is up to $35pC/m^3$ at the cloud edge; the charge per droplet is typically a few electrons, depending on the drop size. These charges are sufficient to influence collision processes between cloud droplets in stratiform clouds and thus, perhaps, to affect the weather and climate.

Harrison et al. [16] discussed how radon emanating from the ground in larger amounts than usual before a major earthquake increases the atmospheric conductivity in the lowest ~ 250m of the atmosphere. Before a major earthquake, therefore, the surface to ionosphere resistance is reduced and, in the fair weather region, the current to the ionosphere increases. The increased current, i.e. the increased upflow of negative ions, has the effect of lowering the ionosphere, and changes the cut-off frequency (~ 1.7kHz) of the Earth-ionosphere waveguide. This process explains the interesting pre-earthquake observations made recently aboard the French micro-satellite Demeter [17].

III. SUGGESTIONS FOR FUTURE RESEARCH

Here we make some suggestions for worthwhile studies in this field of research.

(a) It is essential to devise experimental tests of the suggestion that thunderclouds and electrified shower/rain clouds contribute almost equally to the generator part of the global electric circuit.
(b) An area ripe for further experimental studies is the effect of low level (stratiform clouds), together with their microphysical processes such as electro-activation and electro-scavenging, on the fair weather (load) part of the global circuit. This is especially important in the light of ~ 10% variations in the fluxes of galactic cosmic rays (which cause the ionization in the atmosphere above the boundary layer) over the eleven year solar cycle and during a Forbush decrease.
(c) Improved models of the global circuit, including cosmic ray variations, and solar wind and magnetospheric inputs,

should be constructed; these models should also include stratospheric aerosols and cloud cover of different types.

(d) The energy densities of the various phenomena involved at different altitudes should be investigated.

(e) Land and ocean differences in global atmospheric electric circuit phenomena should be studied in more detail.

(f) It would be interesting to search for signatures in the vertical electric field (magnitude ~ 130V/m) and the fair weather current density observed near the Earth's surface at "meteorologically quiet" times during Forbush decreases of incoming galactic cosmic ray fluxes, to solar proton events, coronal mass ejection (CME) events, and to gigantic jets (which are rare upward discharges between a thundercloud top and the ionosphere).

(g) Coordinated measurements should be made on the ground, in the atmosphere, and from satellites (such as ASIM on the ISS, Chibis, Firefly, Sprite-sat2, and Taranis) to study the effects of sprites and TGFs on the atmosphere and on the near-Earth space environment.

(h) Experimental observations should be devised to test the hypothesis that radon emanating from the land before an earthquake lowers the ionosphere (on a time scale of ~ hours), because that might lead to a practical way of forecasting earthquakes on that time scale.

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