Modeling changes of the ionospheric potential due to lightning and sprites

M. J. Rycroft
CAESAR Consultancy,
35 Millington Road,
Cambridge CB3 9HW, U. K.
michaelrycroft@btinternet.com

A. Odzimek
Institute of Geophysics PAS,
Ksiecia Janusza 64,
01-452 Warsaw, Poland
aodzimek@igf.edu.pl

***Abstract*—An analog electrical engineering model of the global atmospheric electric circuit has been constructed with thunderstorms and electrified rain clouds as generators. This has been used to estimate changes to the ionospheric potential (~ 250kV) due to lightning and sprites. It has been found that this change is: (i) +3.7V for a negative cloud-to-ground (CG) discharge having a typical return stroke current of 30 kA, (ii) –43V for a typical positive CG discharge with a 2kA continuing current lasting 90 ms, (iii) –2.3V for an intra-cloud discharge, and (iv) –1.0V for a sprite.**

Keywords-global circuit model, ionospheric potential, lightning discharges, sprites

I. INTRODUCTION

The Earth's D.C. global atmospheric electric circuit has been the subject of several overview papers in the last ten years or so – see [1-3]. Wave (A.C.) aspects have been reviewed by Siingh et al. [4]. At this URSI General Assembly, Rycroft and Harrison [5] provide an up-to-date summary of both D.C. and A.C. aspects. Two specialist books covering the topic have also been published recently [6,7].

Rycroft et al. [8] and Rycroft and Odzimek [9-10] have described an electrical engineering model of the global circuit created using the *PSpice* software package. An essential property of the atmosphere in the circuit model [8] is provided by the height profile of the electrical conductivity; the value of this parameter rises from ~ 10^{-14} S/m at the surface to 10^{-7} S/m at 80 km. The current generators are thunderclouds and electrified shower/rain clouds, which maintain the ionosphere at a high potential (~ 250kV) with respect to the Earth.

One of the ~ 1000 thunderstorms active around the world at all times is represented as cylinder of the atmosphere, of 10km radius, and resistive layers in parallel with capacitances that are 1km thick, from the surface up to the ionosphere at 80 km altitude [8]. There is a negative charge of –26C at the bottom of the thundercloud at 5 km altitude, and a positive charge of +14C at the top at 15 km altitude. The potential at the bottom of the cloud is –140MV and +6MV at the top. Within this thunderstorm there is an internal upward current of 0.65A; the current flowing up to the ionosphere is ~ 0.3A [8].

The ~ 1000 thunderstorms active over 0.06% of the Earth's surface generate an upward current to the ionosphere of ~ 600A, with ~ 400A being provided by the action of electrified rain/shower clouds over ~ 2% of the surface. Thus the total current flowing around the circuit is ~ 1 kA [8].

In papers [8-10], the authors presented results obtained on the effects of lightning and sprites on the electric potential of the ionosphere, some of which are summarized here.

II. SUMMARY OF RESULTS OBTAINED

To simulate a lightning discharge transferring negative charge from the bottom of the cloud to ground, termed a –CG discharge, voltage-controlled switches are placed in parallel with the thunderstorm. These change their resistance to simulate either the return stroke (RS) or the continuing current (CC) in the discharge. In a –CG discharge, –6.2C is transferred to ground by a 30 kA RS lasting 0.2ms. In order to simulate a +CG discharge, the polarity of the thunderstorm is simply inverted. In such a +CG discharge, + 67C is transferred to ground by the RS and a CC ~ 2kA lasting 90ms [8]. These values of lightning currents are representative of those produced by middle latitude thunderstorms, using data on lightning strikes to an instrumented metal tower in Switzerland – they are the median values reported by Berger et al. [11].

The left hand side of Fig.1 shows a model of the current flowing in a –CG and a +CG discharge and, on the right, the consequent change of the potential of the ionosphere above them [9]. The upper panel represents a –CG having a RS of 30 kA followed by a short (20ms) CC of only ~ 0.2kA. The panel to the right shows the change in the ionospheric potential as a function of time after the discharge. The maximum effect, of +3.7V, is felt ~ 20s after the discharge. The potential recovers to its initial value with an e-folding time of ~ 200s; this is the *RC* time constant of the global circuit [1,5].

The lower part of Fig. 1 shows the situation for a +CG with a short CC (dashed line) and with a long (90ms) CC (solid line). The longer CC causes an order of magnitude larger change to the ionospheric potential (43V) [9]. The time constants are as for changes following the –CG discharge.

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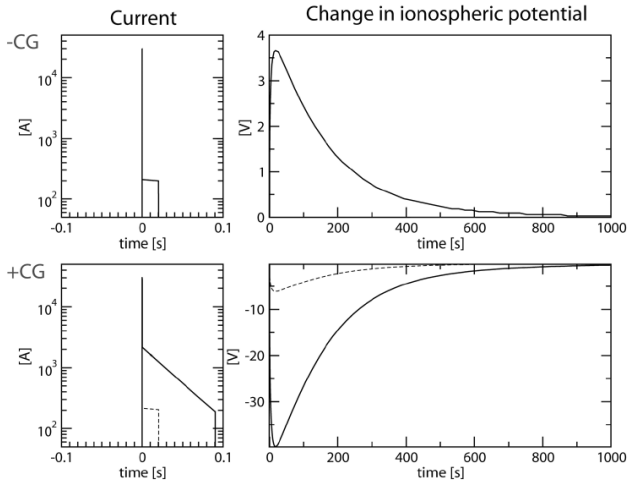

Figure 1. Model negative (upper) and positive (lower) lightning discharge currents (left), and their effects on the ionospheric potential (right).

In their most recent paper, Rycroft and Odzimek [10] used a slightly different atmospheric conductivity profile, specified for a certain date (21 September 2005). This model has the possibility of altering the ionospheric potential by varying the conductivity change in the thundercloud in order to change the properties of the thundercloud generator. In this newer model, the thunderstorms generate 540A and the electrified rain/shower clouds 480A; the total current flowing in the global circuit is therefore 1020A. They also considered the charge moment change (the product of the charge transferred and its height); for the +CG discharge; this was 335C.km.

Using a new high resolution global circuit model, Odzimek at al. [12] have estimated that thunderstorms generate 80% of the total current flowing, with electrified shower/rain clouds providing only 20%. However, the relative contributions of these two generators have not been precisely determined yet. Further experimental and modeling studies are required to make progress on this significant issue.

Intra-cloud (IC) discharges were also considered by Rycroft and Odzimek [10]. Within 0.2ms, a current of ~ 10kA transfers 2C from the bottom to the top of the thundercloud. The charge moment change is therefore 20C.km. The change in the ionospheric potential is found to be 2.3V.

Considering the relative numbers of the different types of lightning discharges, Rycroft and Odzimek [10] showed that, for 44 lightning discharges/s worldwide on average [13], 33/s are ICs, 10/s are –CGs and 0.7/s are +CGs. These cause currents of (2x33) – (7x10) + (67x0.7)A = 66 -70 + 47 = 43A to flow up to the ionosphere. This net current is small compared with the total current ~ 1000A flowing in the circuit. It is therefore concluded that lightning contributes very little (~ 4%) to maintaining the high potential of the ionosphere.

Rycroft et al. [8] and Rycroft and Odzimek [9,10], in a similar fashion, modeled the transient currents flowing in a

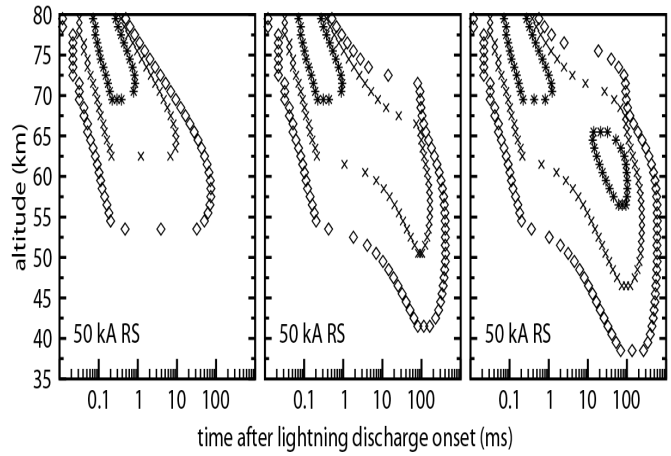

Figure 2. Diagram illustrating the temporal development of a column sprite within the dark starred area from 80km down to 68 km which occurs a fraction of 1ms after a large +CG discharge; the right hand panel shows the development of a "carrot" sprite from 67km down to 57km some tens of ms after the discharge. The region of upward going negative streamer regions is bounded by crosses, and that of downward going positive streamer regions by diamonds.

highly conducting sprite. They showed that long lasting CCs in a +CG cause the breakdown field to be exceeded in the mesosphere after a sufficiently large +CG discharge. With a RS of 50kA and a CC of 0.2kA, 0.5kA and 2kA, this happens within the dark starred areas shown in the three panels (from left to right) of Fig. 2. Starting from the bottom of the ionosphere and down to 68km, a model column (columniform) sprite is generated. Further, from 10ms to ~100ms following this large lightning discharge, with a CC of 2kA, a "carrot" sprite is created from ~66km down to ~ 57km; this region is again shown within the dark starred area. Diamonds show the region where downward propagating positive streamers occur, creating tendrils. On the other hand, crosses show the region where upward propagating negative streamers occur; these are believed to be responsible for the "foliage" often apparent in good quality images of sprites [14].

Rycroft and Odzimek [10] showed that the +CG RS must exceed 35kA to create a column sprite, and that a charge moment change exceeding ~ 350C.km is needed to generate both "foliage" on a "carrot" sprite at 70km altitude and downward developing tendrils. They discussed the start and stop times at which the breakdown threshold field is exceeded at 80, 70 and 60km altitude as a function of the charge moment change. All their results are found to be in general accord with a broad range of observations made by several different techniques. We conclude that the model used is both a realistic and a valuable model.

Fig. 11 of [10] shows the change in the ionospheric potential due to a 30kA, 2kA CC model +CG discharge (as for the lower right panel of Fig. 1, but covering up to only 0.1s after the discharge), together with that for such a discharge followed by a model sprite. The difference between the curves is only 1V. The model sprite current approaches 10kA and lasts for 8ms. The spectrum of the sprite radiation is therefore

expected to peak at frequencies >100Hz. The sprite transfers ~ 40C from the ionosphere; it is therefore equivalent to a charge moment change of ~ 2000C.km.

This entire subject is ripe for further investigations, to be made by experiment and by numerical modeling.

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