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In situ measurements of contributions to the global electrical circuit by a thunderstorm in southeastern Brazil

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ABSTRACT

The global electrical circuit, which maintains a potential of about 280 kV between the earth and the ionosphere, is thought to be driven mainly by thunderstorms and lightning. However, very few in situ measurements of electrical current above thunderstorms have been successfully obtained. In this paper, we present dc to very low frequency electric fields and atmospheric conductivity measured in the stratosphere (30–35 km altitude) above an active thunderstorm in southeastern Brazil. From these measurements, we estimate the mean quasi-static conduction current during the storm period to be 2.5±1.25 A. Additionally, we examine the transient conduction currents following a large positive cloud-to-ground (+CG) lightning flash and typical −CG flashes. We find that the majority of the total current is attributed to the quasi-static thundercloud charge, rather than lightning, which supports the classical Wilson model for the global electrical circuit.

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1. Introduction

The global electrical circuit can be thought of as a leaky spherical capacitor, where the earth's surface is the negatively charged inner shell and the earth's ionosphere is the positively charged outer layer. Since the atmospheric conductivity is low, but non-zero (about $10^{14}(\Omega m)^{-1}$), near the earth's surface and increases exponentially with height, most of the positive charge in the atmosphere resides near the surface (90% within 5 km). The global circuit maintains a potential of 150–600 kV (mean of about 280 kV) between the earth and the bottom of the D region ionosphere at 60–90 km altitude, which results in a fair weather vertical electric field of about −100 V/m near the earth's surface (Roble and Tzur, 1986) (note that here and throughout this analysis a positive electric field indicates the direction of motion of a positive test charge). Since these fair weather charges remain quasi-stable over time, a driving mechanism must exist that supports this charge distribution and the resulting fair weather electric field. Without a driving mechanism, the earth-ionosphere capacitor would discharge in less than 1 h (Roble and Tzur, 1986).

Wilson (1920) first suggested that thunderstorms support this global electric circuit by driving positive charge upwards to the ionosphere and negative charge downwards to the earth's surface. The simple dipole model of a thunderstorm, with a positive over negative charge structure, would drive charge in the proper direction to keep the earth-ionosphere capacitor charged in this manner. If all active thunderstorms on earth at any give time, about 1500–2000, each generated about 1 A of current, this would be enough to drive the global current of 750–2000 A (Roble and Tzur, 1986). But it is unclear how much current each storm actually drives since there have only been a handful of in situ measurements. See Williams (2009—this issue) in this issue for a complete review of the global circuit.

For a nearly uniform electric potential to form between the ground and the ionosphere globally, as is the case in the global circuit, the positive charge driven upward must reach an altitude high enough such that it can easily be distributed horizontally. If we assume that the charge moving through the stratosphere or mesosphere reaches the ionosphere, we can use in situ measurements above thunderstorms to investigate

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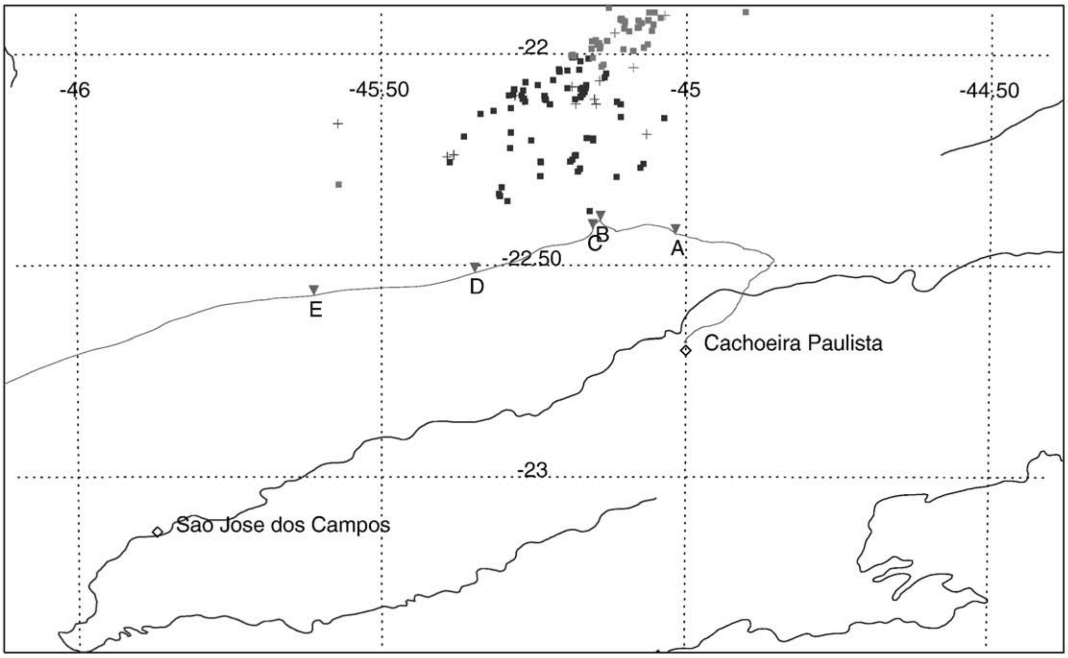

Fig. 1. Flight 1 balloon trajectory, along with lightning strokes (+ for +CGs, and boxes for −CGs) recorded by the BIN Network within 50 km (dark shading) and 100 km (light shading) of the balloon position for 23:20 to 01:00 UT Dec. 6–7, 2002. The labels A–E indicate the balloon location at times 23:23, 23:45, 00:00, 00:30, and 01:00 UT.

their contribution to the global circuit. One cannot make a similar assumption at the ground because charge can accumulate in the troposphere and then return to earth without having reached the ionosphere. Ground-based charge transfer estimates from nearby electric field measurements (Krider and Musser, 1982; Deaver and Krider, 1991) and remote low frequency radio techniques (Cummer and Uman, 2000; Sato et al., 2003) provide an alternate means to estimate the above storm current. However, one must do careful measurements of steady current flows from ground to cloud, track all the lightning charge transfers, and then combine all these terms together. The sum of these terms is balanced by charge that has accumulated at cloud altitudes plus charge that reaches the ionosphere. Hence, ground-based techniques, which involve a balance of many uncertain terms and indirect calculation, cannot achieve the accuracy of direct measurements above thunderstorms.

The first electric field measurements above thunderstorms were obtained by Gish and Wait (1950) in 1948 by flying an instrumented aircraft over 21 thunderstorms in the midwest of the United States, at an altitude of 12 km. During the 1950s, Stergis et al. (1957) launched 25 balloons to 21–27 km over active thunderstorms in central Florida. These early experiments measured dc electric fields directed upwards over thunderstorms that varied with lightning activity. In addition to measuring electric fields, these experiments measured the atmospheric conductivity, which allowed for the calculation of the conduction current density ($J=\sigma E$) above storms. Gish and Wait (1950) and Stergis et al. (1957) estimated the average total upward current to be 0.5 and 1.3 A, respectively, which was the first experimental support for the Wilson (1920) thunderstorm hypothesis for the global electric circuit.

Subsequent balloon-, aircraft-, and rocket-based measurements of electric fields and conductivity above thunderstorms have been conducted. Most of these generally agreed with the previous work of Gish and Wait (1950) and Stergis et al. (1957) by observing charge moving upward above the storms. High-altitude balloon-borne experiments measured upward directed fields up to a few tens of V/m at altitudes of about 25–37 km (Benbrook et al., 1974; Bering et al., 1980; Holzworth, 1981). Using 13 sounding balloon flights below 20 km, Marshall and Stolzenburg (2001) measured the electric field just above convective and stratiform storm regions and found an average voltage of +25 MV relative to the earth. Aircraft flyovers of thunderstorms at 20 km altitude measured fields up to 5 kV/m and upward directed conduction currents that averaged about 1.7 A (Blakeslee et al., 1989). Rocket-borne electric field and conductivity measurements have been conducted above thunderstorms since the early 1980s (Hale et al., 1981; Maynard et al., 1981; Kelley et al., 1985; Barnum, 1999), with lightning-driven field changes of tens of mV/m measured in the mesosphere and ionosphere.

In this paper, we use in situ measurements in the stratosphere of electric field and conductivity to investigate the contribution of a moderately sized thunderstorm to the global circuit. The high time resolution and large dynamic range of these electric field data allow us to compare the relative contributions of static thundercloud charge and lightning transients.

2. The Sprite Brazil Balloon Campaign 2002–03

We use data acquired during the Sprite Balloon Campaign 2002–03 in southeastern Brazil. The objective of this campaign was to obtain in situ measurements, in the stratosphere, of the electromagnetic signature above sprite producing thunderstorms. We observed electric and magnetic field changes driven by thousands of lightning events, including some of the largest vector electric fields ever measured over intense thunderstorms