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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 $10^{14}(\Omega\text{m})^{-1}$), 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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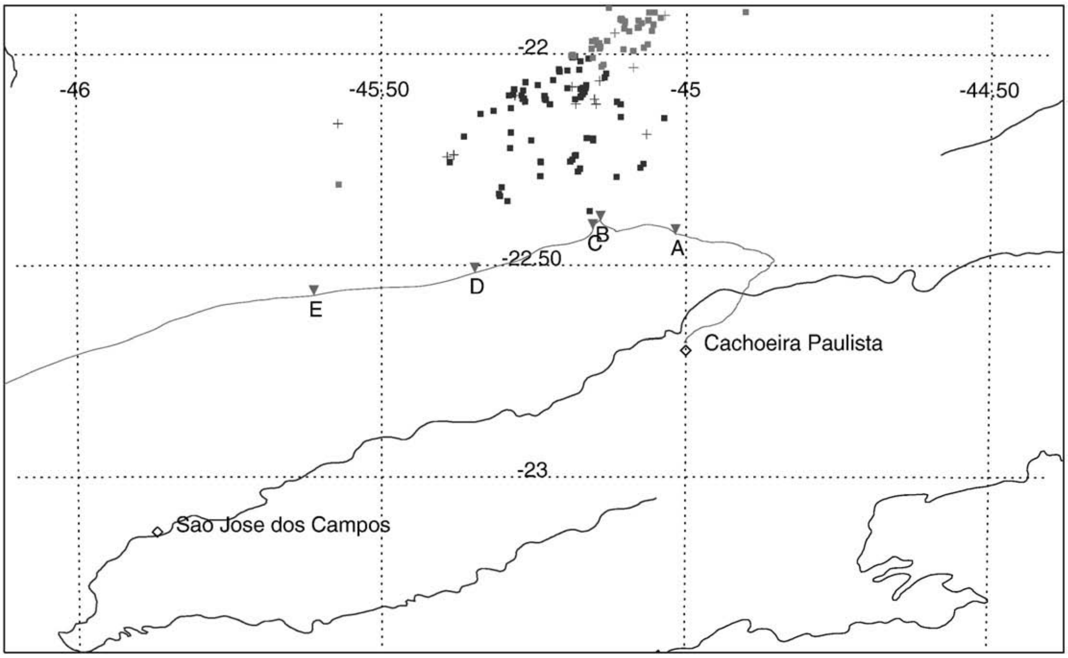

Fig. 1. Flight 1 balloon trajectory, along with lightning strokes (+ for +CGs, and boxes for −CGs) recorded by the BIN Network within 50 km (dark shading) and 100 km (light shading) of the balloon position for 23:20 to 01:00 UT Dec. 6–7, 2002. The labels A–E indicate the balloon location at times 23:23, 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 above 30 km in the stratosphere (see Holzworth et al., 2005, Thomas, 2005, Thomas et al., 2004, 2005). In this analysis, we use the electric field (dc to 10 kHz) and conductivity measurements from Flight 1 of this campaign to calculate the conduction current density above the thunderstorms. The Low-Voltage (LV) and High-Voltage (HV) electric field instruments measured vector fields from dc to 10 kHz with a dynamic range of a few mV/m to 195 V/m via the double Langmuir probe technique (Thomas et al., 2004). The LV vertical sensor was also used to measure the electrical conductivity of the atmosphere every 10 min using the relaxation technique (Holzworth and Bering, 1998). We also use lightning location and peak current data from the Brazilian Integrated Lightning Network (BIN). Note that sprites were not confirmed, since extensive cloud coverage blocked the ground- and aircraft-based sprite imaging cameras during Flight 1.

Brazil Sprite Flight 1 was launched from Cachoeira Paulista, Brazil (22°44′S, 44°56′W) at approximately 22:00:00 UT (20:00:00 local time) Dec. 6, 2002. The payload reached an altitude of about 30 km at 23:23:00 UT and stayed between 30 and 35 km for the duration of the flight until telemetry was lost at 10:49:00 UT Dec. 7, when the payload was downrange 426 km from the ground station. Fig. 1 shows the balloon trajectory with its location at times 23:23, 23:45, 00:00, 00:30, and 01:00 UT indicated by labels A–E. Here we also show CG lightning detected by the ground-based Brazilian Integrated Network (BIN) within 100 km of the balloon location during 23:20 to 01:00 UT. Fig. 2 is a GOES8 IR satellite image at 23:45:00 UT Dec. 6, 2007 of southeastern Brazil with a magnification of the particular storm cell that Flight 1 flew over from about 23:20:00 Dec. 6 to 00:45:00 UT Dec. 7. The labels A–E indicate the balloon location at the times given in Fig. 1. After Flight 1 reached altitudes above 30 km, most of the nearby (< 100 km) lightning events were generated by this cell, which had an area of about 13,000 km^2. These events can be seen on Fig. 1 as the large cluster of lightning north–northwest of the launch site at Cachoeira Paulista.

3. Electrical current due to quasi-static cloud charge

We can use these in situ electric field and conductivity measurements to investigate the contribution of the quasi-static cloud charge to the global electrical circuit. Fig. 3 (left axis) shows the quasi-dc (<25 Hz) vertical electric field measured by the HV instrument during Flight 1 from 23:20 to 01:00 UT at a float altitude of 30–35 km, where a positive electric field represents a field vector directed upward. The maximum quasi-static vertical electric field during the thunderstorm was near 43 V/m and the average field from 23:20–00:20 was about 22 V/m. We also measured one

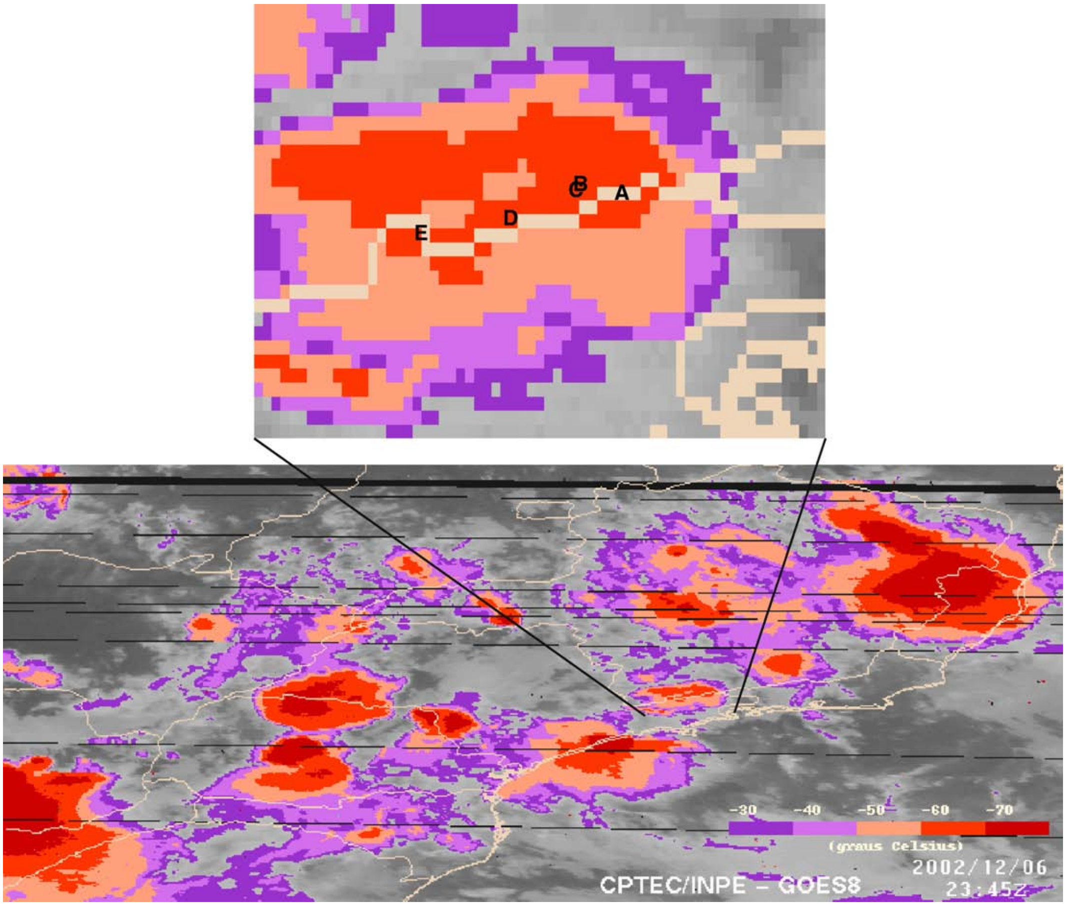

Fig. 2. GOES8 IR satellite image of southeastern Brazil at 23:45:00 UT Dec. 6, 2002 (courtesy of CPTEC, Brazil). The storm cell that Flight 1 flew over is magnified and the labels A–E indicate the balloon location at times 23:23, 23:45, 00:00, 00:30, and 01:00 UT.

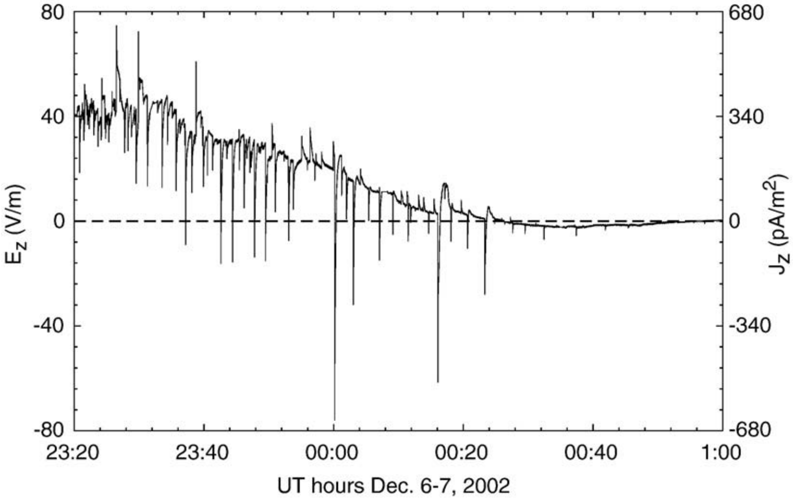

Fig. 3. Vertical electric field measured by the HV instrument (left *y*-axis) and the calculated vertical current density (right *y*-axis) aloft at 30–35 km altitude above and near an active thunderstorm.

component of the horizontal electric field (not shown), which had an average magnitude of about 7 V/m for this storm. The upward spikes are transients driven by negative cloud-to-ground lightning (−CG) and the downward spikes are transients driven by positive cloud-to-ground (+CG) lightning or cloud discharges. The largest field changes occurred at about 00:00:09 and 00:16:03 UT and were correlated with +CG flashes measured by BIN. For this entire flight, the +CG and cloud discharge field changes were generally larger than the −CG field changes, which is apparent in Fig. 3 (left axis). During the end of the storm, at about 00:30, the quasi-static electric field briefly switched polarity to a few V/m negative.

Fig. 4 shows a sampling of one conductivity point (both polarities) every 10 min for 00:00 to 08:00 UT using the relaxation technique. The low voltage vertical probes were momentarily biased with ±2.5 V and allowed to refloat. The decay time to ambient field levels gives a nearly direct measure of the conductivity (Holzworth et al., 1986). Each point is derived from the high time resolution telemetry data, which includes hundreds of data points in each decay profile, resulting in excellent exponential fits to determine the decay time constants. The error in this fitting process results in error bars which are about the size of the point symbols, where we see that the polar components of conductivity (+ for positive and − for negative) have average values of about $3.0\times10^{-12}(\Omega\text{m})^{-1}$, while the total conductivity on average is twice this value (open diamonds). Moreover, each decay curve was individually inspected to be sure that it is not perturbed by a simultaneous lightning stroke. The high voltage probes were not biased and were not used for making conductivity measurements. Therefore conductivity measurements are only available when the low voltage probes were not saturated, and thus positive (negative) conductivity measurements began at 00:20 (00:30) UT. In this analysis, we assume that the total conductivity during the storm (23:20–00:20 UT) was $8.5\times10^{-12}(\Omega\text{m})^{-1}$, which is twice the positive conductivity measured at 00:20 UT.

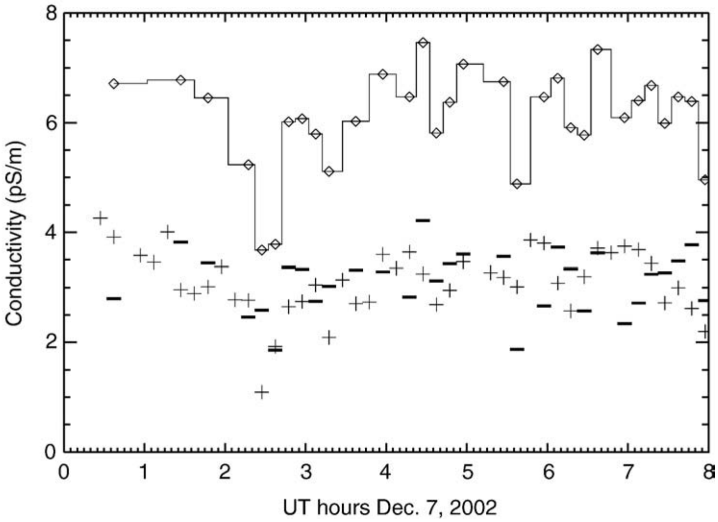

Fig. 4. Polar components of conductivity (+ for positive and − for negative) and total conductivity (open diamonds) at 30–35 km altitude. Note that 1 pS/m = $10^{-12}(\Omega\text{m})^{-1}$.

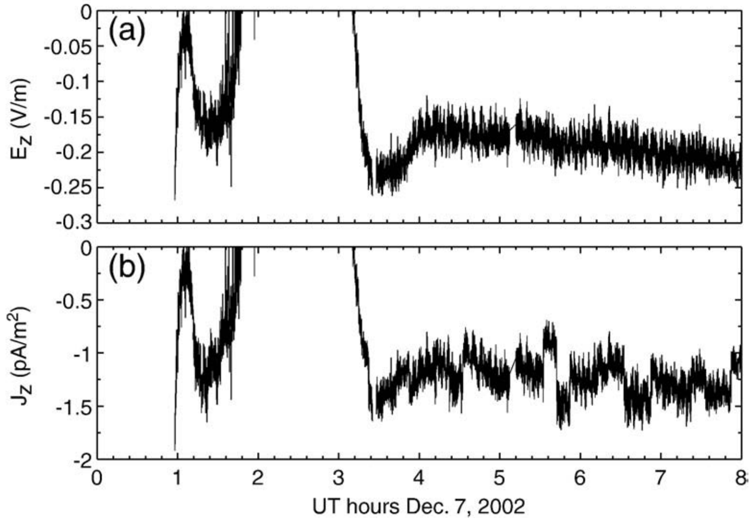

Fig. 5. Vertical electric field measured by the LV sensor (a) and calculated vertical current density (b) at 30–35 km altitude. After about 03:30 UT there was no nearby thunderstorm activity and the field and current density return to typical fair weather value of −150 to −200 mV/m and −1.0 to −1.5 pA/m^2.

Using these vertical electric field and conductivity measurements, we calculate the conduction current density via Ohm's Law ($J=\sigma E$). Fig. 3 (right axis) shows the conduction current density for 23:20 to 01:00 UT, where a positive current represents a current flowing upwards from the cloud to the ionosphere. The maximum quasi-static vertical current density was about 365 pA/m^2 and the average for the storm (23:20–00:20) was about 190 pA/m^2, directed upwards. In order to plot the electric field and current density together, we use $8.5\times10^{-12}(\Omega\text{m})^{-1}$ as the total conductivity for the entire segment presented in Fig. 3. As shown in Fig. 4, the total conductivity is about $6.75\times10^{-12}(\Omega\text{m})^{-1}$ from 00:30 to 01:00. Thus the current density for 00:30 to 01:00 as shown in Fig. 3 is overestimated by about 20%.

To examine the electric field and current density after the thunderstorms subsided, we use data measured by the LV instrument. Fig. 5 shows the vertical electric field measured by the LV sensor (a) and the calculated vertical current density (b) at 30–35 km altitude for 00:00 to 08:00 UT. From about 01:50 to 03:10 UT the field and current density are off-scale due to a storm more than about 75 km away from the payload. During fair weather, after about 03:30 UT, the field and current density returned to typical fair weather values of −150 to −250 mV/m and −1.0 to −1.5 pA/m^2.

We use the infrared (IR) GOES satellite image, BIN lightning location data, and a numerical quasi-static electric field model (Thomas et al., 2005; Thomas, 2005) to extrapolate these point measurements of conduction current density (Fig. 3) into total current and total charge transferred for the storm during 23:20 to 00:20 UT. This numerical model is based on the work of Pasko et al. (1997), and it uses the background and cloud charge densities to solve for the electric field using the Poisson equation (Thomas et al., 2005, Eq. (1)). To model the time-dependent response of the atmosphere, the background charge density is evolved in time by a modified continuity equation (Thomas et al., 2005, Eq. (2)). From the GOES IR image (Fig. 2), we estimate the storm area to be about 13,000 km^2, or approximately circular cross-section with a radius of 65 km. The BIN lightning data indicates that the average horizontal distance from the balloon payload to the CG strokes in this storm was about 27 km. Thus, assuming that the lightning activity was centered at the storm's convective core, the balloon payload was about 27 km from center of the storm.

We first find the input parameters that best fit the model to the in situ measurements. The best-fit cloud charge density is two disks of charge with 100 C at 6 km and −100 C at 4 km altitude. The disks have a surface area equal to the cloud size of 13,000 km^2 and a thickness of 1 km. The atmospheric conductivity profile employed in Thomas et al. (2005) for this same storm is again used here. After inputting the best-fit parameters, we use the model output to estimate the electric field above the entire storm from 20 to 80 km in altitude. At the balloon altitude (~33 km), we estimate the average vertical electric field above the storm area to be about 22 V/m. It is coincidental that the average vertical field estimated from the model is equal to the average field measured.

To find the total current above the storm, we simply multiply together the average vertical electric field of 22 V/m above the storm, the conductivity of $8.5\times10^{-12}(\Omega\text{m})^{-1}$, and the storm area of 13,000 km^2. We estimate that the total current flowing upwards from the storm was about 2.5±1.25 A, which charged the global circuit. We use twice the positive conductivity at 00:20 UT in Fig. 4 because the LV probes were saturated and could not be used to measure the conductivity during the strongest, nearby storm activity. We can integrate over the one hour period of the storm by multiplying 2.5±1.25 A by 3600 s to get 9000±4500 C, which is the total charge transferred from the thundercloud to the middle and upper atmosphere above the balloon altitude. Note that we use a rough estimate of the uncertainty as ±50%, which is mostly due to errors in estimating the cloud size and the model-data comparison.

4. Electrical current due to lightning transients

To analyze the role of lightning-driven electric fields in the global circuit, we examine the transient conduction currents following a large positive cloud-to-ground (+CG) lightning flash and typical −CG flashes. Fig. 6 (left *y*-axis) shows the quasi-dc (<25 Hz) electric field excursion following a +CG flash that included at least two return strokes of +15 and +53 kA at a horizontal distance of about 34 km as determined by BIN. The maximum magnitude of the field excursion was nearly 80 V/m, and the average value was approximately 29 V/m, directed downwards. Thomas et al. (2005) best fit this electric field change to a numerical quasi-static field model (same model as used in Section 3) and found that the charge moment change was about 500 C-km with positive charge removed from an area with cross-sectional radius of about 30 km. Using this model-data comparison, we estimate that the average electric field over the effective cloud area was about 44 V/m for the duration of the transient.

Fig. 6 (right *y*-axis) shows the vertical conduction current density for this positive flash. This was found by multiplying the electric field transient for the +CG flash by the conductivity at 00:20 UT (about $8.5\times10^{-12}(\Omega\text{m})^{-1}$ or twice the positive conductivity). The maximum magnitude of the current density was nearly 700 pA/m^2 and the average was about 250 pA/m^2, directed downwards. Using the average electric field from the model-data comparison, we estimate that the average current density over the effective area of the storm was about 375 pA/m^2 ($44\text{ V/m}\times8.5\times10^{-12}(\Omega\text{m})^{-1}$). We multiply this average current density by the effective area of 2800 km^2 (circular cross-section with radius of 30 km) and the 13 second field relaxation time to calculate charge transfer. We find that the +CG flash transferred about −15 C of charge from the thundercloud to altitudes above the balloon, which discharged the global circuit. Large +CG flashes were rare in this storm, with only two occurring in the one hour period. Hence, the overall charge removal contribution of large +CG flashes to the global circuit was small.

We also analyze typical −CG flashes and find that only 1–5 C of charge were transferred to altitudes above the balloon, which weakly charged the global circuit. This is because the typical electric field transient driven by −CG flashes (about 5 V/m) was much smaller than for +CG flashes. Fig. 7 shows the electric field and calculated current density for a −CG flash consisting of at least one return stroke with a peak current −72 kA located about 39 km horizontal distance from the balloon payload. This electric field transient, with a magnitude of about 11 V/m, was one of the largest in our data set that was driven by a −CG flash. The average current density during this transient was about 230 pA/m^2, which was about 65 pA/m^2 above the background current density due to the static thundercloud charge. As for the +CG flash discussed above, we estimate the total charge transferred during the −CG flash to be 3–4 C using the best-fit model-data comparison. During the storm, 203 −CG flashes were located by BIN. Thus, the overall contribution of −CG flashes was about 200–1000 C of charging to the global circuit using our estimate of 1–5 C per flash.

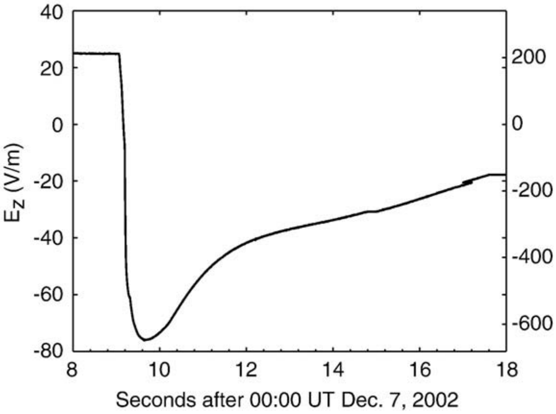

Fig. 6. Vertical electric field (left *y*-axis) and vertical current density (right *y*-axis) at 34 km altitude driven by a positive cloud-to-ground lightning flash with at least two return stokes with peak currents of +15 and +53 kA located at a distance of about 34 km.

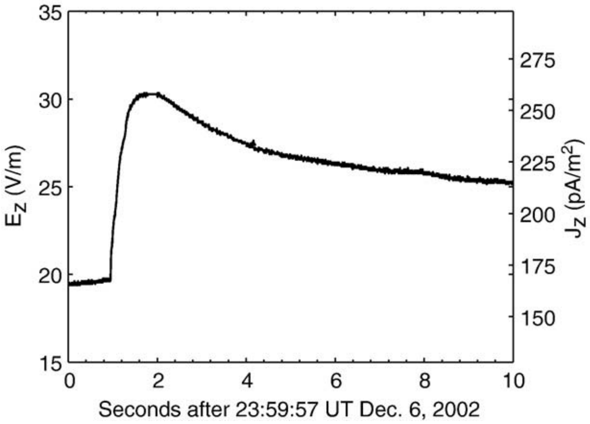

Fig. 7. Vertical electric field (left *y*-axis) and vertical current density (right *y*-axis) at 34 km altitude driven by a negative cloud-to-ground lightning flash with at least one return stoke with a peak current of −72 kA located at a distance of about 39 km.

There were 28 large (>10 V/m) vertical electric field changes measured during Flight 1 that were not detected by the BIN. These electric field transients were downward, which is consistent with +CG flashes or cloud discharges. This suggests that cloud discharges and/or certain +CG lightning with unusual waveforms, which are not located by lightning networks, can drive large electric field transients. In fact, using the method outlined above for the +CG flash, each of these large field changes would discharge the global circuit by 5–15 C. However, since we do not know the horizontal distance to these events, there is considerable uncertainty in this estimate. Nonetheless, cloud lightning or low peak current +CG flashes might be important for discharging the global circuit. We estimate the total contribution due to these events to be about 100–500 C of discharging to the global circuit.

5. Discussion and conclusions

We have not yet considered how our case study storm compares with other storms in southeastern Brazil and other regions of the globe in terms of parameters such as cloud shield area, cloud-top temperatures, and lightning rate. Our case study is a 13,000 km^2 nocturnal storm with a flash rate of about 200 CG strokes per hour. This storm developed as a result of atmospheric instability driven by remnants of a passing cold front (see http://www.cptec.inpe.br/infoclima/2003/jan_2003.shtml). Generally speaking, these frontal system storms occur about 1–2 times per week during the spring, summer and fall in southeastern Brazil (Pinto et al., 2003). The most typical thunderstorms in this region are smaller, air mass storms, which usually have cloud shields less than about 1000 km^2. Air mass thunderstorms are also very typical in most of the other global lightning regions, and they tend to occur around 16:00 to 18:00 local time due to diurnal variations in solar heating (for southeastern Brazil see Pinto et al. (2003, Fig. 8); for other global regions see Rakov and Uman (2003) and references therein). Although larger than an air mass storm, our case study storm is not exceptionally large and is well below the 100,000 km^2 cloud shield threshold for a mesoscale convective complex (Maddox, 1980). Additionally, the flash rate of 3 per minute and cloud-top temperatures of −60 to −70 C of our storm are generally in agreement with observations in other global regions (Rakov and Uman, 2003). Thus, our storm can generally be described as moderate in cloud shield area and typical in flash rate and cloud-top temperatures.

We estimate the average current over our case study thunderstorm to be 2.5 ± 1.25 A, which transferred 9000 ± 4500 C of charge above the balloon altitude of about 33 km. This is within the range of previous measurements and about 1.5–5 times higher than the average current measured at 12–27 km by Gish and Wait (1950), Stergis et al. (1957), and Blakeslee et al. (1989). One explanation for this difference could be that the Brazil storm we investigated was larger than the US storms of the earlier studies. We do not know the size of the storms studied by Stergis et al. (1957) and Blakeslee et al. (1989). However, if we presume that they were typical air mass thunderstorms that formed during summer afternoons, it is very likely that they were smaller than the Brazil storm. Another possible explanation is that the Brazil storm was similar in size, but had a higher charge density compared with the US storms. Extrapolating our measurements to a global perspective, it would take about 300–800 storms like our case study to drive the total current in the global circuit of 750–2000 A. Assuming a 3 to 1 ratio of cloud discharges to CG strokes (Rakov and Uman, 2003), we estimate that about 800 lightning events occurred during one hour of our case study storm, which translates to a flash rate of about 0.2 per second. Using observations from the space-borne Optical Transient Detector, Christian et al. (2003) estimated the global lightning flash rate as 44 ± 5 per second. Hence, about 200 storms like this one would be needed to generate the global flash rate, which is just below our electric current-based estimate of 300–800 storms.

We also examine the contribution of lightning-driven electric field transients on the global circuit. We determine that a large charge moment change +CG flash discharged the global circuit by about −15 C in 13 s. Only two of these large charge moment change +CG flashes, with polarity confirmed by BIN, occurred during the storm. Thus, the overall contribution to the global circuit was small. However, we observed 28 field changes greater than 10 V/m that were not located by BIN. These could be due to either cloud lightning or +CG flashes with unusual waveforms and/or low peak currents. Combined, these flashes could discharge the global circuit by 100–500 C for this storm. In investigating typical −CG flashes, we find that they transferred only a few coulombs of charge upwards per flash and yielded a total contribution of 200–1000 C for this storm.

Our case study suggests that quasi-static thundercloud charge, not lightning, is the primary driving mechanism for the global electrical circuit, which is in agreement with the classical Wilson model. Moreover, since the −CG flashes provide charging and +CG/cloud flashes provide discharging of nearly equal magnitudes, we conjecture that the combined contribution due to all lightning could be very small. Our findings highlight the need for additional in situ measurements above thunderstorms to further test these hypotheses.

Acknowledgments

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