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Stratospheric balloon measurements of electric fields associated with thunderstorms and lightning in Brazil

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Abstract. Measurements of electric fields associated with thunderstorms and lightning were obtained during two balloon flights carrying double-probe electric field detectors launched from Cachoeira Paulista (22°44′S, 44°56′W), Brazil, on January 26, 1994, and March 23, 1995. From data obtained in 1994, a linear relationship between the quasi-dc vertical electric field peak amplitude and the decay time constant of lightning signatures was found for negative flashes. The results are compared to similar data for intracloud flashes. Based on electric field data obtained in 1995 and on the present knowledge about the differences between positive cloud-to-ground and intracloud flashes, two methods to distinguish them at balloon altitudes are presented: The first is based on an estimate of the destroyed charge in the event; the second is based on the peak amplitude ratio between the vertical quasi-dc and the VLF electric field. The behavior of the vertical quasi-dc electric field before and after large cloud-to-ground lightning flashes is discussed and attributed to the existence of a shielding layer around the thunderstorm. This shielding layer is associated with a threefold or greater decrease in the conductivity inside the cloud. An abrupt variation observed in the quasi-dc electric field possibly associated with the occurrence of positive flashes was observed and attributed to the formation of a transient shielding layer just above the thunderstorm, which could be produced by the near-breakdown field inside the cloud.

1. Introduction

The knowledge of the electrical processes inside a thunderstorm and how they affect the middle atmosphere has been the goal of many research projects [*Park and Dejnakarintra*, 1973; *Bering et al.*, 1980; *Stolzenburg et al.*, 1998]. At present, the research of electric field variations over thunderstorms is of even greater importance in order to understand some new phenomena occurring at these altitudes.

The electrical charge structure of thunderstorms has long been believed to be either a vertical positive dipole, with a positive charge above a negative charge, or a tripole, with a lower positive charge region added below the dipole. Recent in situ measurements are not in accord with either the dipole or tripole charge model. *Marshall and Rust* [1991] reported on 12 balloon soundings through thunderstorms; all their soundings had at least four charge regions. Although the storm may have multiple centers of charge, the picture of a positive dipole still seems to be valid at large distances from the storm, and the electric field appearing at high altitudes after the charge removal by cloud-to-ground lightning discharge can be defined mostly by the absolute value and altitude of the removed charge. The charge removal can also be viewed as the "placement" of an identical charge of opposite sign. The initial field above the cloud is simply the free space field due to the "newly placed" charge and its image in the ground, which is assumed to be perfectly conducting [*Hu*, 1994; *Pasko et al.*, 1997].

The electric conductivity in the clouds is controlled by the local balance of sources and sinks. The dominant sink is caused by cloud and aerosol particles, which reduce the electric conductivity within the clouds by a factor of about 10 compared with the fair weather value because the small ions tend to become attached to the cloud particles. The difference in conductivity between clear air and a cloud causes a layer of space charge to form on the boundary between the cloud and clear air [*Volland*, 1984]. This layer has been observed in the past, and it is called the "screening layer" [*Byrne et al.*, 1989; *Marshall et al.*, 1989].

In the stratosphere the vertical electric field associated with thunderstorms is well known to be characterized by an inversion with respect to the fair weather field [*Gish and Wait*, 1950; *Stergis et al.*, 1957; *Benbrook et al.*, 1974; *Bering et al.*, 1980; *Holzworth*, 1981; *Holzworth et al.*, 1986; *Pinto et al.*, 1988; *Hu et al.*, 1989; *Pinto et al.*, 1992a; *Hu*, 1994]. On the other hand, to date very few in situ measurements of stratospheric vertical electric field associated with lightning flashes have been published [e.g., *Benbrook et al.*, 1974; *Burke*, 1975; *Bering et al.*, 1980; *Holzworth and Chiu*, 1982; *Pinto et al.*, 1992b].

The vertical electric field in the stratosphere associated with lightning flashes has a typical signature of a sferic, that is, a rapid variation followed by a tail which lasts less than 10 s. Although the recovery curve (i.e., the return to the previous ambient field) depends on the local conductivity, it has a time constant different from the ambient relaxation time, indicating that it is probably also influenced by electric charging processes inside the thundercloud which are not well understood. Another interesting remark in all previously mentioned measurements is that no changes were observed in the value of the ambient dc electric field before or after the

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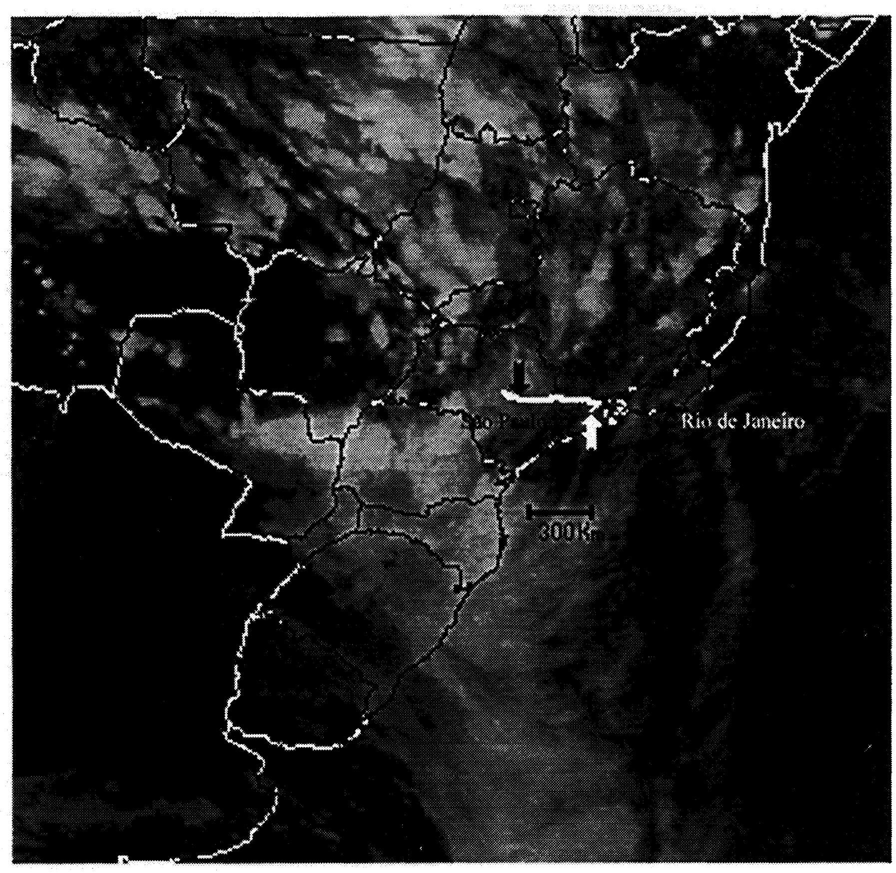

Figure 1. Meteosat IR image, 1900 LT, March 23, 1995. The black and the white arrows indicate the position of the balloon and the launching site location, respectively. The trajectory is also shown.

occurrence of lightning. This fact is further evidence, among others already published, of the existence of the screening layer.

In general, the direction of perturbation of the stratospheric electric field is used to determine the polarity of the cloud-to-ground lightning flash. If this perturbation is an intensification of the inverted electric field (upward electric field), the lightning polarity is said to be negative; otherwise it can be positive [*Holzworth*, 1981; *Holzworth and Chiu*, 1982]. At the same time, it is normally assumed that the field changes associated with intracloud flashes have lower amplitude than those associated with cloud-to-ground flashes, even though no upper limit to the amplitude of the intracloud-related field changes is defined.

This paper presents a variety of stratospheric electric field measurements associated with thunderstorms and lightning. Lightning-related field change measurements were obtained during two stratospheric balloon flights launched from Cachoeira Paulista (22°44′S, 44°56′W), Brazil, on January 26, 1994, and March 23, 1995. We discuss the above criterion to identify the polarity of the flash and suggest new ones to discriminate positive cloud-to-ground flashes from intracloud flashes. The advantage of these new criteria is that they do not need to establish an arbitrary upper limit for intracloud field change amplitude. We also present data showing a linear relationship between the peak amplitude and the decay time constant of lightning field changes for cloud-to-ground flashes that may give some hints on charging processes. We discuss the electric field data obtained before and after lightning field changes associated with two lightning flashes, invoking the existence of shielding layers around the thunderstorm to explain them. All the balloon data analysis was supported by satellite and radar data.

2. Experimental Setup

The zero-pressure balloon-borne payload in both flights was equipped with a vertical double-probe electric field detector to measure the vertical quasi-dc electric field [*Kellog and Weed*, 1969; *Mozer and Serlin*, 1969; *Benbrook et al.*, 1974; *Bering et al.*, 1980; *Holzworth*, 1981]. It consists of two Aquadag-coated spherical conductors separated by a high resistance 1.73-m boom. In this experiment the probes were 20-cm-radius aluminum spheres with a capacitance of about 22 pF. They were connected to a very high input impedance electronic circuit. One of the spheres was used as an antenna to measure the 5 to 200-kHz VLF electric field. The data were sampled every 50 ms using two different gains (0.25 and 2.5). The electric field measured with these two gains was accurate to 50 mV/m and 5 mV/m, respectively. Pressure and temperature sensors and a Global Positioning System were also present in the payloads [*Saba et al.*, 1999]. The balloons were tracked throughout each flight, and thunderstorm systems were identified by satellite and radar images.

On January 26, 1994, a 7500-m^3 balloon was launched at 0720 LT (1020 UT). During its drift westward, at an average altitude of 27.5 km, the balloon passed over two thunderclouds, registering several lightning-related field changes.

On March 23, 1995, a 54,000-m^3 balloon was launched at 1335 LT and drifted westward, as usual in this period of the year. During the flight, at an altitude of 32 km, it registered three lightning-related field changes with amplitude higher than 1.5 V/m. One of these had an amplitude of 6.3 V/m, which is very intense considering the balloon altitude. Figure 1 shows one Meteosat satellite infrared image approximately 10 min after the occurrence of the flashes. The trajectory, the position of the balloon, and the location of the launching site are also shown in this figure. Radar data were used to estimate the probable location of the charge center in the thundercloud and the balloon distance from the thundercloud.

3. Results

3.1. Polarity of Lightning Flashes

Figure 2 shows three lightning field changes (named N1, P1, and P2) obtained in 1995 associated with an isolated thunderstorm. The figure shows the vertical quasi-dc electric field (dc) and the 5 to 200-kHz VLF (ac) electric field produced by each lightning field change. At first glance, it would be possible to determine the polarity of the parent flash from the direction of the quasi-dc electric field change. However, this is only true if the balloon is inside a certain distance from the thundercloud, named herein as "inversion distance". Considering the Coulombian character of the electric field perturbation (see next paragraph) caused by charge destruction associated with the lightning flash, the direction of the lightning field change reverses if the balloon is beyond that distance (see Figure 3). In order to calculate the inversion distance, one must know the altitude of the payload and estimate the heights of the charge center or centers that may have originated the flash. The heights of the charge centers and the distance from the balloon to the thunderstorm were estimated using radar data and on-board GPS. Although some imprecision is implicit in these estimates, it was possible to find out that N1 was generated by a negative cloud-to-ground flash, whereas P1 and P2 were generated by positive cloud-to-ground or intracloud flashes. P1 and P2 were determined to be associated with positive cloud-to-ground flashes based on two methods: first, the charge destroyed by the flashes, estimated from the quasi-dc electric field; and second, the ratio between the quasi-dc and the VLF fields.

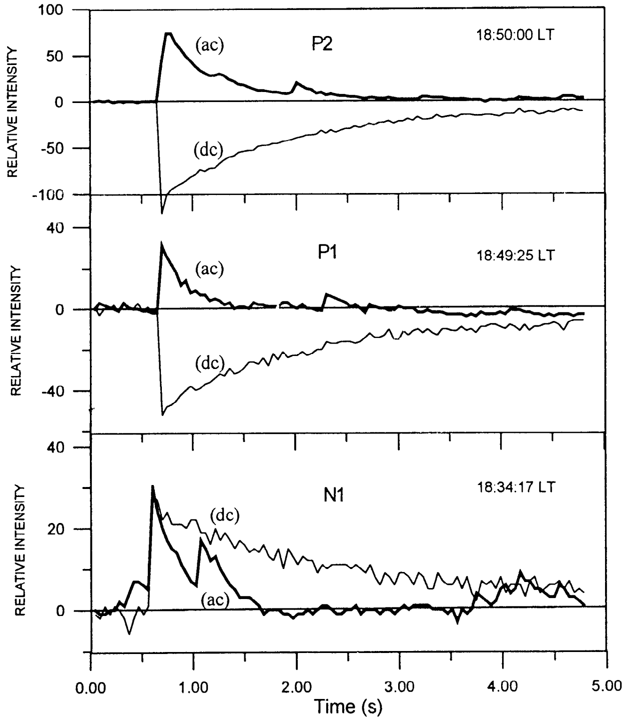

Figure 2. Three lightning field changes registered in the vertical quasi-dc (dc) and VLF (ac) electric field data obtained on March 23, 1995. Thick lines indicate the VLF (ac) field.

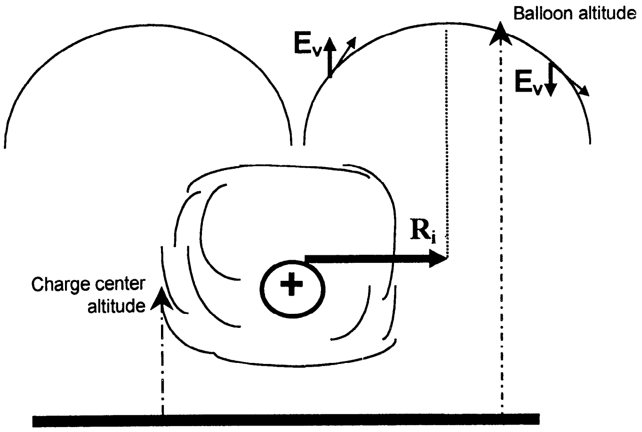

Figure 3. Electric field model of a negative cloud-to-ground lightning and R_i, the inversion distance.

3.1.1. Destroyed charges. The amount of charge destroyed in the flashes was roughly estimated from the peak values of the vertical quasi-dc field change using the Coulomb law equation. This is a valid approximation considering that the lightning events experienced at the balloon can be assumed to be dominated by the electrostatic field component because the balloon was always no more than 40 km from the source region [*Burke*, 1975]. Considering also that the charge removal caused by a lightning discharge occurs on a timescale much less than the relaxation time of the stratosphere, we are supposing that the peak amplitude of the transient is not significantly reduced by the conductivity of the medium [*Anderson and Freier*, 1969].

The positive charge inside the cloud was supposed to be located at the height of 7 km, considering that the top of the cloud was estimated by the radar to be around 8 km. The calculated destroyed charge was found to be between 5 and 28 C for P1 and between 12 and 76 C for P2. The large uncertainty is mainly associated with the error in the location of the lightning flash within the thunderstorm. Other sources of errors are the heights of the payload and charge center, which were obtained using data from an on-board GPS and the meteorological radar of Bauru, São Paulo. The cited values of destroyed charges are larger than the normal values (around 1 C) expected for intracloud flashes [*Ogawa*, 1982], while they are of the same order as those associated with positive flashes [*Berger et al.*, 1975]. If any atmospheric conductivity were to be taken in consideration, the estimated values of the destroyed charges would be much higher, giving as a result stronger support to the criterion for flash discrimination above.

3.1.2. Ratio between the quasi-dc and the VLF fields. It is well known that lightning field changes generated by intracloud flashes have a higher spectral frequency content distribution than cloud-to-ground flashes (see, for example, *Krider et al.* [1975] and *Volland* [1984]). Therefore the ratio between peaks of the quasi-dc and the VLF field produced by a cloud-to-ground flash will be higher than the ratio between peaks produced by an intracloud flash. In the case of the lightning field changes in Figure 2, this ratio was found to be 0.93 for N1, 1.68 for P1, and 1.66 for P2. These values are consistent with the assumption that positive flashes normally have longer trajectories in the atmosphere than negative flashes and, consequently, a higher component in low frequencies. The opposite (i.e., lower values of dc/ac for P1 and P2) should be expected if the flashes P1 and P2 were intracloud flashes.

3.2. Relationship Between the Amplitude and Decay Time Constant of Lightning Field Changes

Figure 4 shows the relationship between the amplitude of the field changes associated with negative cloud-to-ground flashes and their decay time constants. Data were obtained on the January 26, 1994, balloon flight. In this flight all observed lightning field changes occurred when the balloon was inside the inversion distance of the thundercloud. So, based on the direction of their signatures, we could say that negative flashes generated them all. Decay time constants were obtained from exponential curve fits for the first 60 data points after the electric field peak amplitude (Figure 5). Care was taken to choose only the lightning transients whose final electric field was nearly equal to the electric field before it occurred. Thus small lightning field changes were not analyzed due to the fluctuations of the ambient electric field. As there is no other published relationship for negative flashes, our results are shown with those obtained by *Burke* [1975] for intracloud flashes (Figure 4). The best fit lines, equations, and correlation coefficients are also presented. In both cases the correlation coefficients are high, although the slopes of the linear equations are very different. Such a different behavior cannot be explained by different ambient conductivity only; it must be associated with the different types of lightning considered in each case, indicating that the temporal variation of the charging process inside the cloud in each case may be quite different for intracloud and cloud-to-ground flashes. In other words, it may depend on the quantity of charge destroyed. It is also worth noting that for large lightning field changes the decay time constant can be higher than the ambient relaxation time constant.

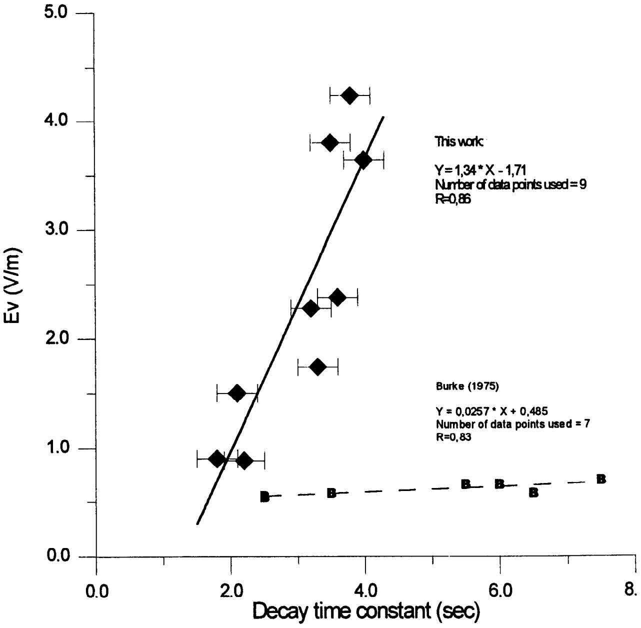

Figure 4. Lightning field change peak amplitude versus decay time constant.

3.3. Behavior of the Ambient Vertical Electric Field During the Occurrence of Lightning-Related Field Changes

Figure 6 shows an 8-min interval of continuous stratospheric vertical electric field data obtained at an altitude of 32 km on March 23, 1995. The two positive cloud-to-ground flashes, P1 and P2, and a third flash (cloud-to-ground or intracloud flash), originating in the same isolated thunderstorm, can be seen in the figure. The third flash remained undefined because considering the extension of the cloud that generated this flash, we could not determine if it occurred at a distance greater or smaller than the inversion distance.

There are two points worth mentioning about Figure 6. First, the average value of the vertical electric field just before and just after the occurrence of P1 and P2 is not altered. This is in agreement with most balloon-borne electric field measurements recorded in the literature. Second, the electric field shows an abrupt increase about 15 s before the first flash (P1). The increase is about 0.28 V/m and remains for about 4.5 min. There is apparently one similar case reported by *Holzworth and Chiu* [1982].

With respect to the first point, the charges destroyed by P1 and P2 should have produced a decrease of at least 0.43 V/m in the vertical field, considering the measured conductivity scale height of 5.2 km [*Saba et al.*, 1999]. This decrease was not observed. Considering the fluctuations in the vertical electric field occurring at this time, changes in the dc level greater than 0.15 V/m would have been noticed. We therefore suppose that a screening layer around the thunderstorm should have reduced the variation of the electric field seen by an external observer. The estimated shielding factor associated with the screening layer would be equal to or greater than 3. Considering that this factor is also related to the ratio between the conductivity inside and outside the thunderstorm [*Volland*, 1984; *Makino and Ogawa*, 1985], we found that the conductivity inside the cloud is lower than that outside by a factor of 3 or more. This value is in reasonable agreement with the few values reported in the literature [e.g., *Volland*, 1984].

The second point related to Figure 6 is the occurrence of an abrupt increase in the electric field about 15 s prior to the first positive flash. It was about 0.28 V/m and remained for about 4.5 min. Although the actual process behind this phenomenon may be very complex, we suggest that this increase may be related to a transient shielding layer just above the cloud. It

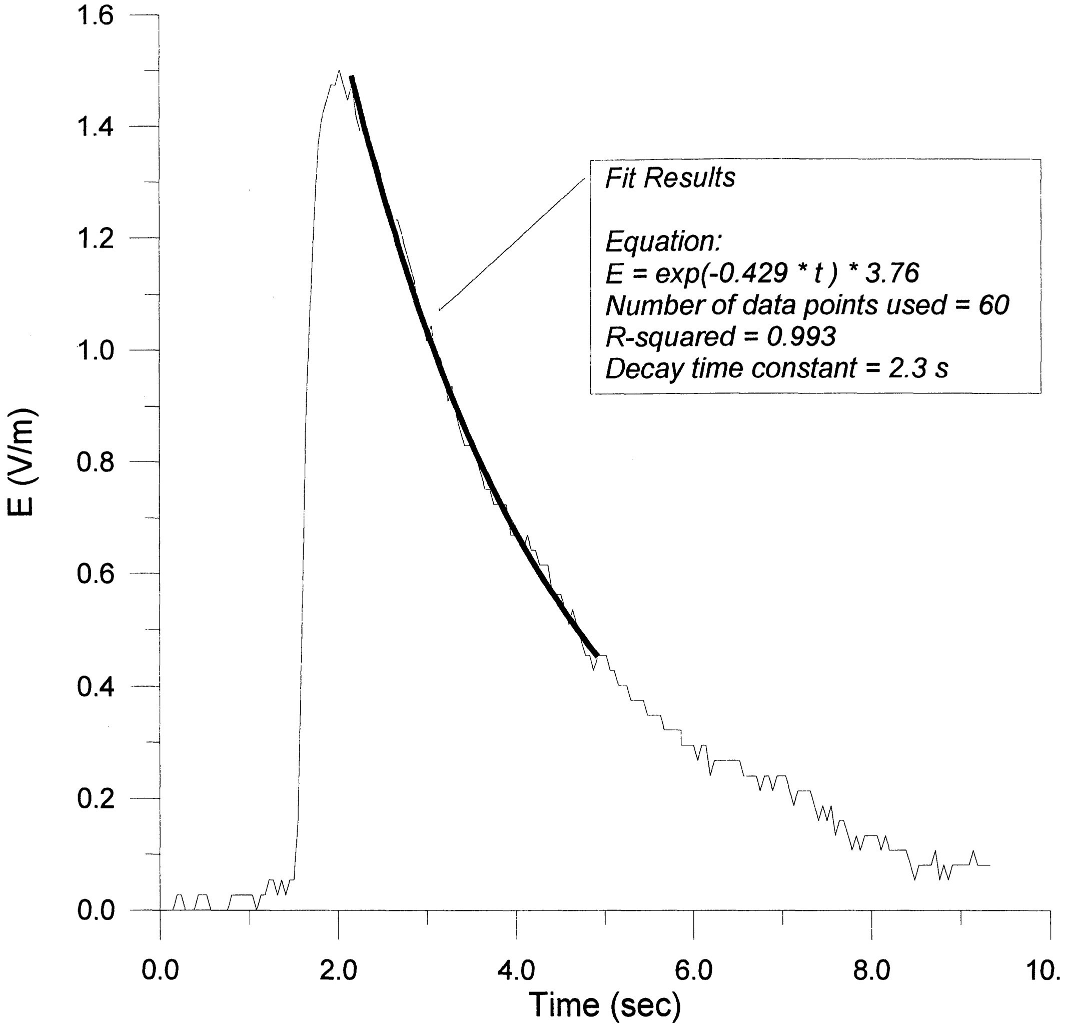

Figure 5. Example of curve fitting of a recovery curve of a lightning field change and its decay time constant. This field change was produced by a negative flash occurring on January 26, 1994 at 1202 LT.

could have been produced as a consequence of the large breakdown field, which is expected to exist inside the cloud just before a cloud-to-ground lightning event. The necessary time for a transient shielding layer to be completely shielded (99%) by the atmospheric charges was estimated by *Brown et al.* [1971] and *Marshall and Lin* [1992] as approximately equal to 5 times the relaxation time constant at the shielding layer altitude. Considering the altitude of the top of the cloud (8 km), a complete shielding would occur at about 5 min. This value is of the same order as the 4.5-min interval indicated in Figure 6. A similar case (with an increase of about 0.3 V/m) seems to have been observed by *Holzworth and Chiu* [1982].

4. Summary

Lightning-related field changes data were obtained in Brazil during two balloon flights. The data and theories concerning the electric field changes associated with thunderclouds are discussed and compared with similar data obtained by other authors.

Two new criteria, based on the destroyed charge and spectral frequency content, were suggested and used to discriminate field changes produced by positive cloud-to-ground flashes from those produced by intracloud flashes. These simple criteria may be helpful in other studies using stratospheric balloons equipped with electric field detectors.

A linear relationship between the amplitude and the decay time constant for negative lightning field changes was found and shown to be different from the same relationship for intracloud field changes. The reason for such a difference is probably related to charging processes inside the thundercloud and remains to be investigated in more detail.

The behavior of the vertical quasi-dc electric field before and after large cloud-to-ground lightning flashes was discussed and attributed to the existence of a shielding layer around the thunderstorm. This shielding layer was associated with a threefold or greater decrease in the conductivity inside the cloud.

An abrupt increase of the vertical electric field about 15 s prior the occurrence of a positive flash was observed and explained assuming an intensification of the electric field inside the thundercloud. Although the intensification of the electric field was associated with large positive cloud-to-ground flashes, we believe that this event is probably not related to sprites since the thundercloud size contradicts the published climatology of sprites [*Sentman et al.*, 1995;

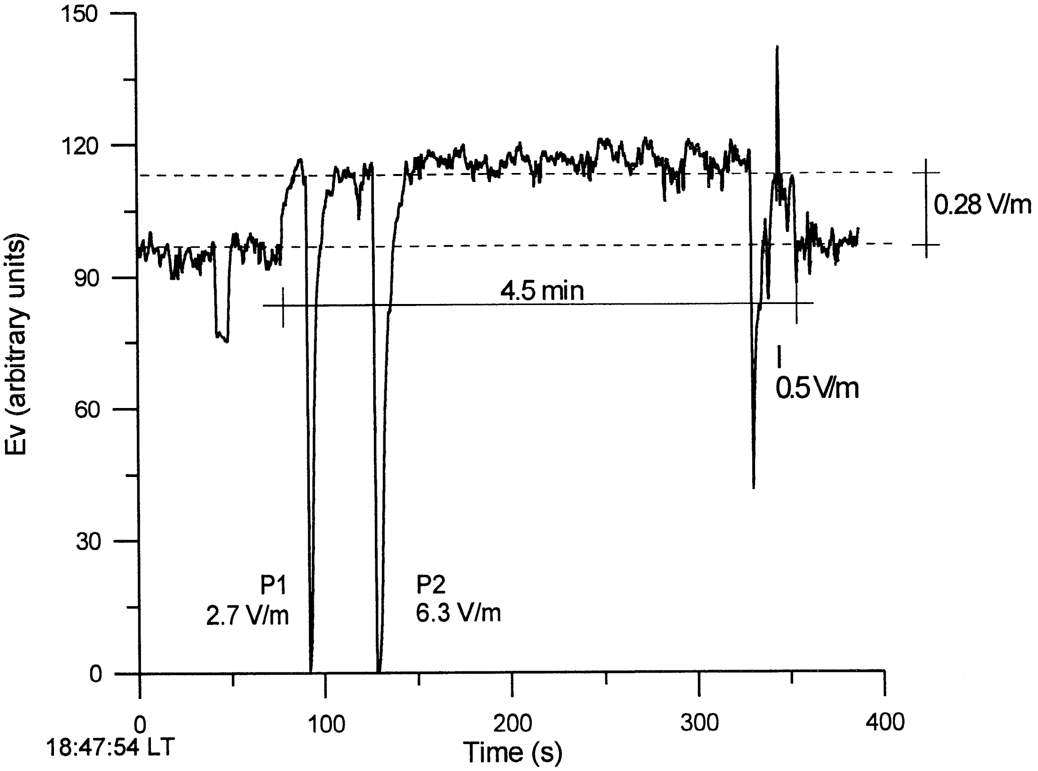

Figure 6. Vertical electric field data obtained on March 23, 1995 (starting at 1847:54 LT), showing three lightning field changes and an abrupt increase around 70 s. The drop around 50 s is due to a conductivity measurement.

Winckler et al., 1996]. However, we think that the abrupt variation of electric field in the stratosphere is a rare enough event worthwhile mentioning, and it may be associated with other similar phenomena that may or may not produce optical emissions. Further balloon studies on the electric field over thunderstorms lowering intense positive charge may prove to be very useful to reason the matter out.

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