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JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES
97: (D16) 18195-18204 NOV 20 1992

Document type: Article **Language:** English Cited References: 35 Times Cited: 4

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KeyWords Plus:
THUNDERSTORM, CONDUCTIVITY, PRECIPITATION

Addresses:
PINTO O, INST NACL PESQUISAS ESPACIAIS, S JOSE CAMPO, SP, BRAZIL.

Publisher:
AMER GEOPHYSICAL UNION, WASHINGTON

IDS Number:
JZ602

ISSN:
0148-0227

Article 6 of 14 PREVIOUS NEXT SUMMARY

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. D16, PAGES 18,195–18,204, NOVEMBER 20, 1992

A COORDINATED STUDY OF A STORM SYSTEM OVER THE SOUTH AMERICAN CONTINENT
1. WEATHER INFORMATION AND QUASI-DC STRATOSPHERIC ELECTRIC FIELD DATA

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Abstract. This paper reports on a coordinated campaign conducted in Brazil, December 13, 1989, to study the electrical signatures associated with a large storm system over the South American continent. Inside the storm, large convective cells developed extending up to the tropopause, as revealed from meteorological balloon soundings. Quasi-DC vertical electric field and temperature were measured by zero-pressure balloon-borne payload launched from Cachoeira Paulista, Brazil. The data were supported by radar and GOES satellite observations, as well as by a lightning position and tracking system (LPATS). The analysis of infrared imagery supports the general tendency for lightning strikes to be near to but not exactly under the coldest cloud tops. In turn, the radar maps located the strikes near to but outside of the most intense areas of precipitation (reflectivity levels above 40 dBz). The balloon altitude and stratospheric temperature show significant variations in association with the storm. The quasi-DC vertical electric field remained almost during the whole flight in a reversed direction relative to the usual fair weather downward orientation with values as large as 4 V/m. A simple calculation based on a static dipole model of electrical cloud structure gives charges of some tens of coulombs. In contrast with most electric field measurements in other regions, no indication of an intensification of the vertical field in the downward fair weather orientation was observed. This fact is in agreement with past observations in the South American region and seems to be related to a particular type of storm that would occur with more frequency in this region. If so, such a difference may have an important role in the global atmospheric electrical circuit, considering that South America is believed to give a significant current contribution to the global circuit.

Introduction

In the last decade there have been a large number of observations of electric fields in the stratosphere due to thunderstorms or other forms of electrified storm systems (Bering et al., 1980; Holzworth, 1981; Holzworth et al., 1985, 1986; Barcus et al., 1986; Pinto et al., 1988; Hu et al., 1989). The main objective of these observations was to study the electrical structures responsible for these fields and their influence on the local stratosphere, as well as on the global atmospheric electric circuit.

In the stratosphere the onset of thunderstorm electrification is indicated when the electric field above the cloud changes its orientation and begins to increase in the anti-fair-weather sense. This can be adequately explained assuming that the cloud has become approximately a vertical dipole with a positive polarity, that is, a positive charge in the upper part and a negative charge in the lower part of the cloud. Another possible representation of the thunderstorm structure considers an electrical tripole. The tripole consists of a dominant region of negative charge located generally in a relatively narrow range of altitudes (actually less than a kilometer) where the temperature is around 10^0-20^0C below freezing (Krehbiel, 1986), with a positive charge region above extending nearly to the cloud top and a more localized region of positive charge below. For most of the investigators the first two charge regions are considered the dominant accumulations of charge in the cloud, or main charge regions, with total charges reported to be from a few coulombs to a few hundred coulombs. Nevertheless, Williams (1989) has pointed out that the lower positive charge region may have a total charge of the same order of magnitude. Beside these regions there are usually two thin layers of charges, negative at the top and positive at the base of the cloud, called screening layers. These layers are formed by ions attracted into the cloud from the adjacent clear air. After entering the cloud, these ions become attached to cloud particles, charging them but becoming effectively immobilized. Larger charges may still exist in localized regions of a storm (Winn et al., 1974). In fact, recent in situ measurements made by Marshall and Rust (1991) have shown that the charge structure is much more complex, being described in some cases by as much as 10 charge centers.

The above description however represents only a simplified picture of how charge is distributed

Paper number 92JD01480.
0148-0227/92/92JD-01480$05.00

in a thunderstorm. The actual charge distribution depends on complex and varied electrical processes that are intimately related to the cloud dynamics and to microphysics of the cloud, which we are only beginning to understand.

The electrical structure of thunderstorms seems also to be related to their convective state. However, there is some uncertainty about the details of such relationship. Some observations show that lightning and precipitation are correlated (e.g., Larsen and Stansbury, 1974; Krehbiel et al., 1979; Taylor et al., 1984; Williams, 1989), whereas other observations show that lightning avoids regions of strong precipitation (Williams, 1985) or occurs before maximum precipitation (Szymanski et al., 1980).

A better understanding of the electrical structure of thunderstorms as well as on their influence on the stratosphere may have important implications in global terms. The electric currents flowing from the top of the thunderstorms to the upper atmosphere maintain the electrically conducting upper atmosphere at a positive potential of several hundred kilovolts with respect to the Earth, giving rise to a global fair weather electric field, in a process known as the global atmospheric electric circuit. Variations in the electrical structure of thunderstorms at different geographic locations may have a direct effect on the intensity of currents flowing in the atmosphere. In particular, this fact could be of increasing importance if it would occur in the tropics (mainly over South America and Africa) where a dominant current contribution to the global circuit is expected.

In this paper the results of a coordinated campaign conducted in Brazil on December 13, 1989, to study the electrical signatures associated with a large storm system are presented but with emphasis on the weather-related information and temperature and quasi-DC electric field stratospheric data. A detailed presentation of the lightning-related stratospheric electric field data (sferics) can be found in part 2 (Pinto et al., this issue). Also found in part 2 is an analysis of the data obtained on the ground by a lightning detection system.

Observations

The observations were conducted in Brazil on December 13, 1989, using several different techniques: (1) a zero-pressure balloon-borne payload carrying an external temperature sensor and an electric field detector. The temperature sensor consisted of a standard LM135 integrated circuit located just below the payload, mounted on a plastic support. The sensor was not shielded to radiation which came from below. The electric field detector was similar to that flown in the past (e.g., Pinto et al., 1988) and consisted of two aquadag-coated spherical sensors (22 cm in diameter) mounted on two high-impedance vertical booms 1.5 m up and down to the payload, which was used as a ground plane. Besides the quasi-DC vertical field a broadband filter centered at 2 kHz was used to measure the VLF electric field. The data were sampled at a 4-Hz rate; (2) synoptic information from a number of weather stations and meteorological balloon soundings; (3) GOES 7 satellite infrared data; (4) meteorological radars; and (5) a lightning position and trackihg system (LPATS).

Figure 1 shows a map of part of Brazil, where the campaign was conducted. In this figure one can identify the balloon trajectory starting at Cachoeira Paulista, geographic coordinates 22°39'S, 45°01'W (the launching site), and the regions covered by the LPATS to the south and west (with an error less than 1-2 km) and by the radars of Baurú and São Roque. The radars operate at 5-cm and 10-cm wavelengths, respectively.

Figure 2 shows synoptic observations at surface from a number of weather stations in Brazil at 1200 UT on December 13, 1989. A low-pressure center (indicated by "B") situated around 21°S, 63°W with a cold front extending south produced a large instability region characterized by a cyclonic circulation at low levels and an anti cyclonic circulation at high levels (300 mbar and above). Figure 3 shows the vertical profiles of air temperature and humidity (dew point temperature) from a radiosonde balloon launched from Cachoeira Paulista at 1400 UT (1200 LT summertime) on December 13, 1989. Two samples of wet adiabats have been included. The tropopause was located at about 17 km altitude. Radar data indicated that inside the storm, vigorous convection carried the cloud tops up to the tropopause, while at the edge of the storm, thunderstorm lines with cloud tops reaching 14 km developed.

The above observations were supported by infrared imagery taken each 30 min from GOES 7 satellite. The infrared data have been processed to yield the equivalent blackbody temperature of the observed features. The results are represented by 14-step colors from 193 K to 258 K, each spanning approximately 4,6 K. This temperature is generally assumed to be a good indicator of the heights to which the cloud tops have risen. For example, Plate 1 shows imagery taken at 1200 UT, 1730 UT, and 1930 UT on December 13, 1989. A large storm system can be identified in the top left-hand portion of the imagery. The storm was progressively advancing south, approaching the balloon (marked by a dot). Using the temperature profile in Figure 3, it is possible to estimate the heights for the cloud tops in the storm system. Based on this

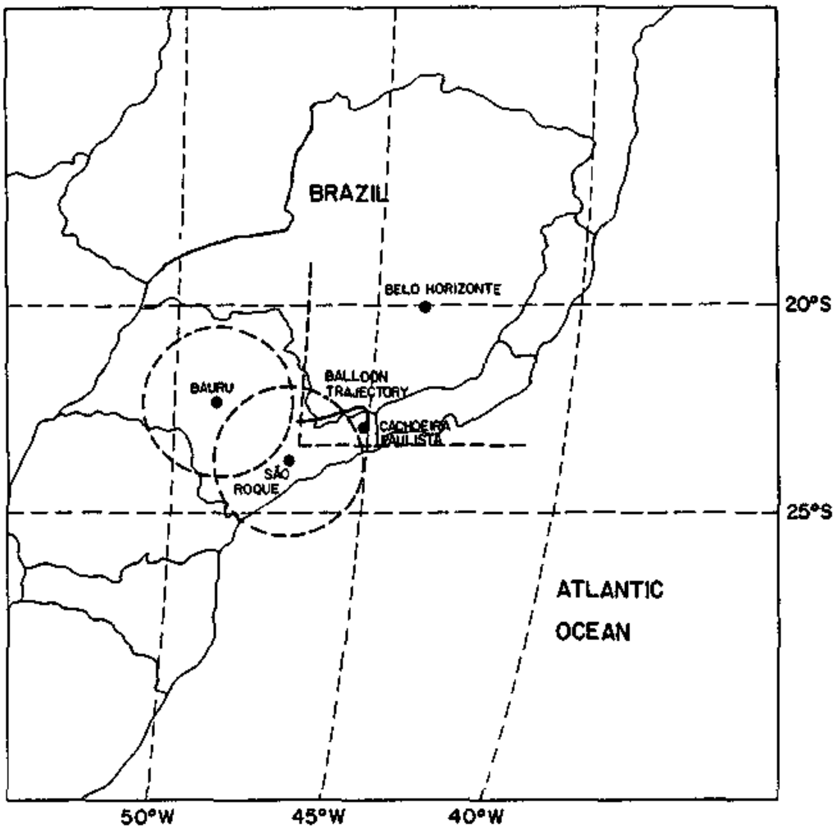


Fig. 1. Map showing part of Brazil where the campaign was conducted. Also shown are the balloon trajectory starting at Cachoeira Paulista (the launching site) and the regions covered by the lightning position and tracking system (LPATS) (lines denote the limits to south and west) and by the meteorological radars of Baurú and São Roque (circles denote 200 km of distance from the radar).

procedure and in agreement with the radar data, it was found that there are extensive cold areas around the center of the storm where the cloud tops are pushed near to the tropopause. In the region close to the balloon the heights of the cloud tops were progressively increasing after 1730 UT. However, there are uncertainties in this procedure of estimating the heights of the cloud tops. The principal uncertainties are associated with the inaccuracy of the temperature profile, the physics of the infrared emissivity of cloud tops, and the finite spatial instrumental resolution. While possible bias due to the first might go either way, the last two lead to an underestimate of the cloud tops. In general, the major error is attributed to the physics of the infrared emissivity of cloud tops, amounting to 1-2 km (Minzner et al., 1978; Adler and Fenn, 1979). However, as we should discuss afterward, such a statement cannot be true in some cases when the spatial resolution is very poor.

Figure 4 shows the balloon trajectory in some details. The balloon was launched at 0920 UT on December 13, 1989, from Cachoeira Paulista, São Paulo, Brazil. Almost 10 hours of data were obtained. During this interval the balloon moved in the direction of the edge of the storm system. Figure 5 presents the results of the balloon measurements. The top panel contains the balloon altitude (or atmospheric pressure). The second panel contains the ambient temperature and the bottom two panels contain the electric field measurements. The fair weather electric field and the time occurrence of the first stroke detected by the LPATS network are indicated by arrows. The data in Figure 5 show clearly two different behaviours, one before and one after approximately 1630 UT. Before this time all data are typically what one would expect of fair weather conditions. In contrast, after 1630 UT all data show effects related to the storm. These two different regimes are also evident in the satellite imagery, which indicate that around 1630 UT the balloon had arrived very close to a thunderstorm line located on the edge of the storm system. The balloon data will be discussed in detail below.

Discussion

There are three points to note about Figure 5. The first point is related to the fact that both

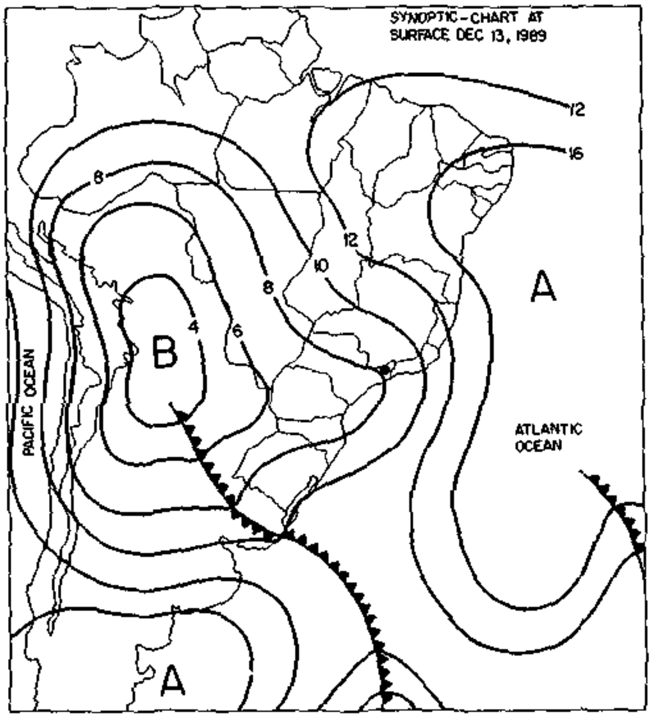


Fig. 2. Synoptic chart at surface, 1200 UT, December 13, 1989. The symbols A and B denote high-pressure and low-pressure regions, respectively. Also indicated is a cold front extending into the Atlantic Ocean. The launching site is indicated by a dot.

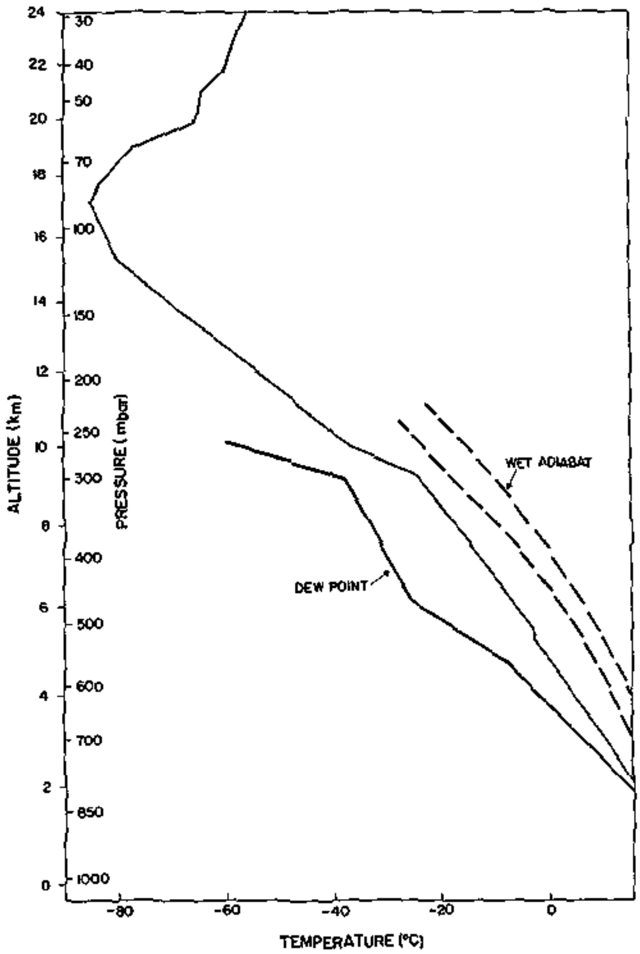


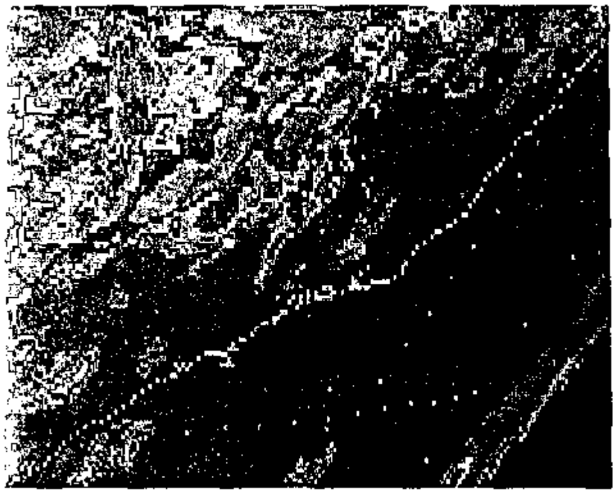
Fig. 3. Vertical profiles of air temperature and humidity (dew point temperature) from a radiosonde balloon launched from Cachoeira Paulista at 1400 UT, December 13, 1989. Two samples of wet adiabats have been included.

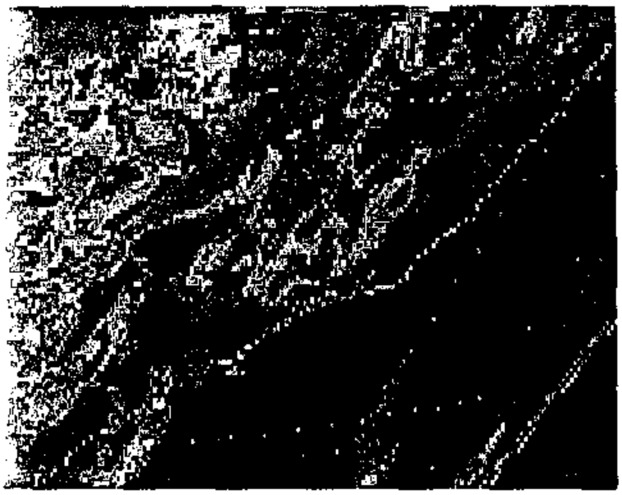
balloon altitude and ambient temperature show significant variations during the period in which the electric field shows thunderstorm-related signatures. During this period the balloon altitude drops from 32 km to 27 km in approximately 3 hours. The temperature also shows a variation by about 5°C during this period but in the opposite sense that one should expect from the corresponding altitude change. These variations suggest that the storm may considerably affect the stratosphere just above it.

Large balloon altitude variations such as those reported in Figure 5 have also been reported by Holzworth (1981) (see Figure 7 of that paper). Such large variations should be considered quite different from the common, slow decline expected at the end of a flight, normally attributed to a wide variety of possible leak generation mechanisms (see, for instance, Byrne et al. (1989)). One possible mechanism to explain the balloon altitude variations reported here is the presence of thunderstorm-generated gravity waves. Several authors have found that high convective clouds with tops in or around the tropopause can develop large gravity waves in the stratosphere (Rottger, 1981; Larsen et al., 1982; Lu et al., 1985; Bowhill and Gnanalingam, 1986). In fact, Byrne et al. (1989) have shown that even during fair weather, gravity waves, probably generated by wind shear instability, can produce balloon altitude changes by as much as 400 m. During foul weather it is reasonable to expect more intense waves in order to produce balloon altitude variations larger than those in fair weather.

Plate 1. Infrared data from GOES 7 satellite processed to show effective blackbody temperatures (14-step color scale 193-258 K) of features observed between approximately 20°-25°S and 40°-50°W at: (a) 1200 UT; (b) 1730 UT; and (c) 1930 UT. Each step spans approximately 4.6 K and is portrayed in a different color. The color scale is shown in the top part of the imagery. The temperature increases from left to right. During this time interval the storm system advanced to the south approaching the balloon (marked by a dot).

The temperature variation shown in Figure 5 is o quite significant, since in the stratosphere temperature tends to be quite uniform with riations that amount to a few degrees in a rizontal scale of thousands of kilometers ring the day. Also, it is expected that





adiabatic vertical motions (that is, decreases with decreasing pressure) generally occur in association with gravity waves. Kitchen and Shutts (1990) have recently shown that the temperature profile in the lower stratosphere can be drastically altered by the presence of orographically forced gravity waves in association with strong low-level winds. Their results give support to the idea that the temperature variation after 1600 UT in Figure 5 may be due to thunderstorm-generated gravity waves.

Another possible mechanism that could be invoked to explain the increase of the temperature as the balloon drops in altitude is related to the solar radiation reflected on the tops of the clouds right below the balloon. It is well documented that the top of large thunderstorms can reflect a large percent (around 70%) of the incident solar radiation (Kreith, 1975). In contrast to the direct solar radiation, the radiation reflected on the top of the clouds could reach the temperature sensor. However, as it can be seen from Plates 1b and 1c (for more details, see also Figures 6 and 7), after 1730 UT the cloud cover as well as the cloud top altitudes changed in such a way that an opposite behaviour from that in Figure 5 would be expected if it was due to the radiation reflected from the top of the clouds. The temperature variation may still be influenced by wake effects associated with the presence of the balloon-payload system (Quinn, 1987). Nevertheless, it is valid to note that these mechanisms could not explain the balloon altitude variation shown in Figure 5.

The second point to note in Figure 5 is that the quasi-DC vertical electric field remains almost the whole flight (actually 7 hours) in a reversed direction relative to the usual fair weather downward orientation, with values as large as 4 V/m. This value is of the same order as those measured by most investigators at high latitudes in the northern hemisphere. Figure 5 also shows no indication of an intensification of the vertical field in the downward fair weather orientation. Table 1 shows a comparison of these results with other electric field measurements in the stratosphere showing the presence of upward vertical electric fields. An attempt was made to include all reported measurements. Table 1 also includes the weather information available at the time of each measurement, the balloon altitude, the maximum upward vertical electric field, and the maximum horizontal electric field measured. From Table 1 one can see that most measurements made at high latitudes in the northern hemisphere as well as those at middle latitudes in the southern hemisphere show the presence of intensification in the fair weather field. Only four out of 17 measurements did not show such intensification, two in Brazil and two near Fort Simpson, Canada. We can also note from Table 1 that these four measurements were associated with

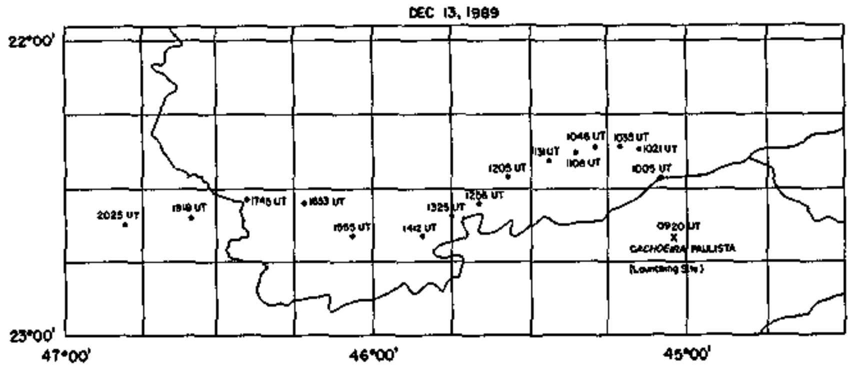


Fig. 4. Trajectory of the balloon launched from Cachoeira Paulista at 0920 UT, December 13, 1989. The solid curve denotes the limit between the states of Sao Paulo and Minas Gerais.

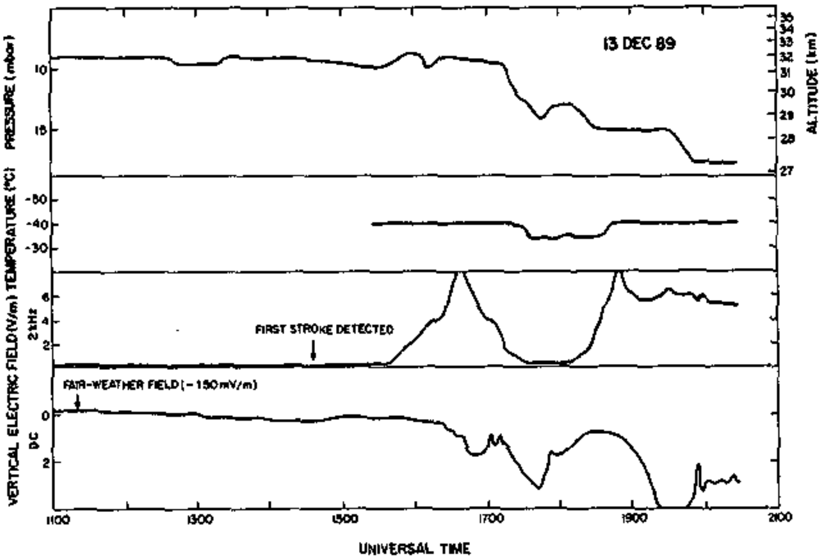


Fig. 5. Almost 10 hours of pressure, temperature, VLF-2kHz electric field and quasi-DC vertical electric field data from the balloon flight indicated in Figure 4. The fair weather electric field and the time occurrence of the first stroke detected by the LPATS are indicated by arrows.

storm systems, even though there were other measurements associated with storms without the presence of intensification. In addition, there is no clear relationship between the fair weather intensification and the presence of lightning-related balloon signatures. At the same time, Table 1 shows clearly that in most cases the weather conditions as well as the balloon location were poorly known. The fact that for both measurements made in Brazil there is no intensification of the fair weather may indicate that some differences in the cloud electrification in this region may exist. If so, such differences may have an important role in the global atmospheric electric circuit, considering that South America is believed to give a significant current contribution to the global circuit. However, from Table 1 it seems more probably that such an aspect should be related to a particular type of storm that occurs in other regions (not only in the South America) although with less frequency.

Although the origin of the fair weather intensification is not clear yet, Pinto et al. (1989) have discussed some possibilities to explain such observed intensifications in the fair weather field during storm periods. They have pointed out that such an aspect can be explained considering a constant convection current density model for the charge structure of the cloud, without the need to invoke a screening layer of negative charges at the top of the cloud or even a negative polarity cloud.

The third point to be made from Figure 5 is that both the quasi-DC and the VLF electric fields show a double-peaked structure, although the peaks do not coincide in time. A similar behaviour also occurred in the measurements made

TABLE 1. Balloon Double-Probe Electric Field Measurements Showing Upward Vertical Electric Fields Possibly Related to Electrified Clouds

Date	Local	Altitude, km	Maximum Upward Field, V/M	Horizontal Fields, V/M	Weather Condition	Occurrence of Fair Weather Intensification	Occurrence of Lightning-Related Balloon Signatures	Reference
August 2, 1969	Uranium City, Canada	28	> 2.5	> 6.5	No complete information (only data from nearby meteorological ground stations).	yes	not mentioned	Mozer [1971]
August 3, 1969	Penhold, Canada	29	0.6	0.5	No complete information (only data from nearby meteorological ground stations).	yes	yes	Burke [1975]
July 10, 1973	Texas, United States	37	> 3	> 0.15	Radar data (thunderstorm line with cloud tops around 10-km distance 10-20 km from balloon.	yes	yes	Benbrook et al. [1974]
August 11, 1974	Fort Simpson, Canada	21-27 (large drop apparently associated with clouds)	1.1	0.05	Incomplete satellite coverage (probably associated with a storm system).	no	no	Holzworth [1981]
August 13, 1974	Fort Simpson, Canada	27	> 6.6	> 1.7	Space satellite coverage (probably associated with a storm system).	no	yes	Holzworth and Chiu [1982]
June 29, 1975	Greenland	25-30	> 2	not shown	No complete information (only data from nearby meteorological ground stations).	yes	not mentioned	Madsen et al. [1983]
July 2, 1975	Greenland	25-30	> 3	not shown	No information.	Undefined (depends on altitude data).	not mentioned	Madsen et al. [1983]
July 9, 1975	Quebec, Canada	35	3	2	Radar data (isolated thunderstorm with cloud tops around 10.5 km from balloon).	yes	yes	Bering et al. [1980]
July 10, 1975	Baffin Island, Canada	25-30	1	0.8	No information.	yes	not mentioned	Madsen et al. [1983]
April 9, 1978	Thompson, Canada	not mentioned	0.5	0.15	Space satellite coverage (probably associated with a storm system).	yes	no	Holzworth [1981]
April 2, 1980	São Paulo, Brazil	26	1	0.5	Satellite and radar data (storm system with electrified clouds with tops around 8.5 km).	no	no	Pinto et al. [1988]
January 20, 1984	44.7°S 156.4°E	26	> 7	2.5	No information.	yes	no data	Holzworth et al. [1986]
February 15, 1984	45.6°S 150.8°E	26	> 7	2.5	No information	yes	yes	Holzworth et al. [1986]
August 11, 1982	Greenland	35	1	no data	Satellite data (storm system with cloud tops up to the tropopause, 10 km).	yes	no	Barcus et al. [1986]
July 31, 1987	Virginia, United States	31	0.3	0.01	Satellite, radar, and lightning ground data (small isolated thunderstorm).	yes	yes	Hu et al. [1989]
July 9, 1988	Virginia, United States	30	> 1.5	0.1	Satellite, radar and lightning ground data (storm system at distances less than 50 km of the balloon).	yes	yes	Hu et al. [1989]
December 13, 1989	São Paulo, Brazil	27-32 (large drop apparently associated with clouds)	> 4	no data	Satellite, radar, and lightning ground data (nesoscale convective system with cloud tops up to the tropopause, 17 km. Balloon passed over clouds with tops up to 11 km).	no	yes	This work

region. Such a fact would have important implications on the global electric circuit, since from this point of view at the time of fair weather intensification the storm would be acting more as a sink than as a source. However, before we can establish the role played by such intensification on the global circuit, more measurements accomplished with more complete weather information should be made.

Acknowledgments. This work was partially supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo-FAPESP. The authors would like to acknowledge the support given by the meteorological group of INPE, in particular Yoshihiro Yamasaki, José Carlos Rodrigues, Manoel Alonso Gan, José Luiz Oliveira, and Nuri Oyamburo de Calbete, by the Companhia Energética de Minas Gerais, in particular Raphael Lisbôa de Araújo and José Henrique Diniz, by the University of Baurú, in particular Regina C.S. da Costa, Maurício de A. Antonio, and Roberto V. Calheiros, by the radar facility of the Brazilian Air Force at São Roque, in particular Captain Tavares, and by the balloon group of INPE. Also, the authors wish to thank Wanderli Kabata and Osvaldo Celso Pontieri for their technical support and Robert Holzworth, Pedro Leite da Silva Dias, Daniel Jean Roger Nordemann and Walter D. Gonzalez for useful comments.

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(Received June 4, 1991;
revised June 15, 1992;
accepted June 22, 1992.)