Friulian Journal of Science **5.** 2004, 37-48

Ground measurements of the Earth Electric Field

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Abstract. This work provides a description and physical interpretation of the Earth's electric field over the plain of Friuli. The electric field is measured by way of a field mill positioned in Ziracco (UD). The field mill records the changes of the electric field every second, both in fair weather and stormy conditions. In fair weather conditions the Earth electric field points toward the ground and has values of the order of 100 Vm^{-1}. In stormy conditions, the Earth electric field magnitude increases rapidly and sudden inversions take place during the atmospheric electrical discharges. After these discharges the electric field returns to its initial values in different ways that still need an exhaustive interpretation. At the end of the storm, a typical trend is revealed. This trend can be interpreted based on the simple tripole model. All these features are analyzed in conjunction with the radar data, in particular with the VMI measurements, and in conjunction with the position of the cloud to ground lightning strikes.

Keywords. Earth electricity, cloud electrification, lightning strikes.

Introduction. The presence of an electric field in the lower atmosphere has been known since the earliest experiments of B. Franklin and L. Lemonnier in the XVIII century (Rakov & Uman 2003). This field generally points towards the Earth surface, supporting the idea that the air has an electrostatic potential higher than the ground. The electric potential increases with height; the difference between the potential at an altitude of about 60 km and that of the ground is about 300 kV, but the

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potential gradient (i.e., the electric field), is significantly different from zero only below 20 km (Markson 1976). A few meters above the ground, in fair weather conditions, the electric field is about 100 V m^{-1}. Air conductivity varies with height, too. In the first 50 km above the Earth surface positive ions and free electrons are produced by means of cosmic rays, solar radiation and natural radioactivity (Gringel et al. 1986). Radioactivity is an important process for ionization in the first kilometer closer to the Earth crust, but over the ocean its action is strongly reduced. Close to the ground, about 10^7 ions m^{-3} s^{-1} are produced. Above one kilometer, ionization is principally due to solar radiation and cosmic rays. In the lower atmosphere, the average time life of free electrons is of the order of micro seconds, while ions can survive for about one hundred seconds, thus they are mainly responsible for the air conductivity in that layer. In the upper atmosphere, that is nearly fifty km above the mean sea level, free electrons are the major contributors to atmosphere conductivity. There are six orders of magnitude between air conductivity above the ground (about 10^{-14} S m^{-1}) and air at 60 km (about 10^{-8} S m^{-1}) (Hale 1984). This difference causes the electric field to decrease with height; in fair weather conditions, its reduction follows an exponential law (Volland 1984) that drops the field to about 300 mV m^{-1} at 30 km (Gringel et al. 1986). Because of its conductivity and the potential gradient, there is a charge transfer from the atmosphere to the ground that is estimated to be a global electric current of about 1 kA. Because of this and the persistence of the Earth electric field, it is necessary to assume the existence of a balancing mechanism bringing positive charges from the ground to the upper atmosphere. Wilson (1920) proposed a capacitor model for the Earth electric circuit which depicts the lower atmosphere as a lossy spherical capacitor in which the Earth surface has a negative charge excess of about $5 \cdot 10^5$ C and the 1 kA current is balanced by the thunderstorms' action. Approximately 10% of the Earth surface is continuously subject to thunderstorms, each one presenting electric activity. It is thus assumed that thunderstorms bring positive charges to the upper atmosphere to preserve the global circuit in a steady-state balance. Supporting this model, long time series of measurements show the correlation between the diurnal variation of the Earth electric field in air weather and the worldwide areas affected by thunderstorms (Whipple 1929 & Harrison 2004). However, the annual variation of the field is not consistent with the annual variation of thunderstorms in the world (Imyanitov & Chubarina 1967). There are also alternative models for the global electric circuit, some of which assume that the Earth is strongly negatively charged (Dolezalek 1988), while according to others thunderstorms only produce local electrical phenomena and do not play an important role in the global electric circuit (Kasemir 1994). So far, even if several general aspects of the electrical properties of the Earth's atmosphere are well understood, there is not a unique robust model explaining the fair-weather electrical field. Thunderstorms locally produce large variations of the Earth electric field. This paper explores measurements of the field at the ground recorded during a stormy day, and field variations are compared with lightning strike records and radar reflectivity images.

Material and methods

1. The instrument. The Earth electric field has been measured by means of an electric field meter (MacGorman & Rust 1998) which is usually called field mill. The instrument was made according to a well known principle (Winn 1993). Free electric charges in the troposphere are driven along the lines of the Earth electric field. Even if the density of the electric current produced is very low (i.e., about $2\ 10^{-12}$ Am^{-2}) it is possible to transform this current in a periodical signal having a low noise to signal ratio and then amplify it. Figure 1 shows a simple scheme of the field mill, Figure 2 shows pictures of the instrument. The project was developed, along with the instrument, in the framework of a very fruitful collaboration between Unione Meteorologica del Friuli Venezia Giulia (UMFVG) and the Regional Meteorological Observatory (OSMER). The field meter operates in the Friuli plane, NE of Italy. Measurement site is in the open country, close to a village (Ziracco) located in the plain, and the field meter is quite far from the influence of artificial or natural vertical structures, like buildings or trees; the surrounding terrain is flat. Calibration of the field meter is done every three months; records are almost continuous time series of the Earth electric field with a time resolution of 1 s. The precision of the measurements is about 20 Vm^{-1}. The northeastern Italian plain is a very interesting meteorological region because its warm season is characterized by thunderstorms. The daily climatological probability for thunderstorms is close to 0.6 in the warm season, that is from April to September (Giaiotti & Stel 2001, Giaiotti & Stel 2002). This weather characteristic provides an opportunity to measure the Earth electric field in the same geographical place, that is at the same conditions, during the occurrence of its significant variations related to meteorological phenomena only.

2. Radar Data. Information from radar reflectivity is used in this work to study the position and the intensity of storm cores. Radar data have been retrieved from the OSMER meteorological radar archive. The radar site is on the shoreline of the Friuli region (Fossalon di Grado) and the radar scans cover completely and continuously the whole plain in which the field meter is operating. A lot of information is available from the scans (Bechini et al. 2001), but for the purposes of thunderstorm cell tracking, the vertical maximum intensity (here, after VMI) has been chosen. VMI is the value of the maximum radar echo recorded from the bottom to the top of the troposphere

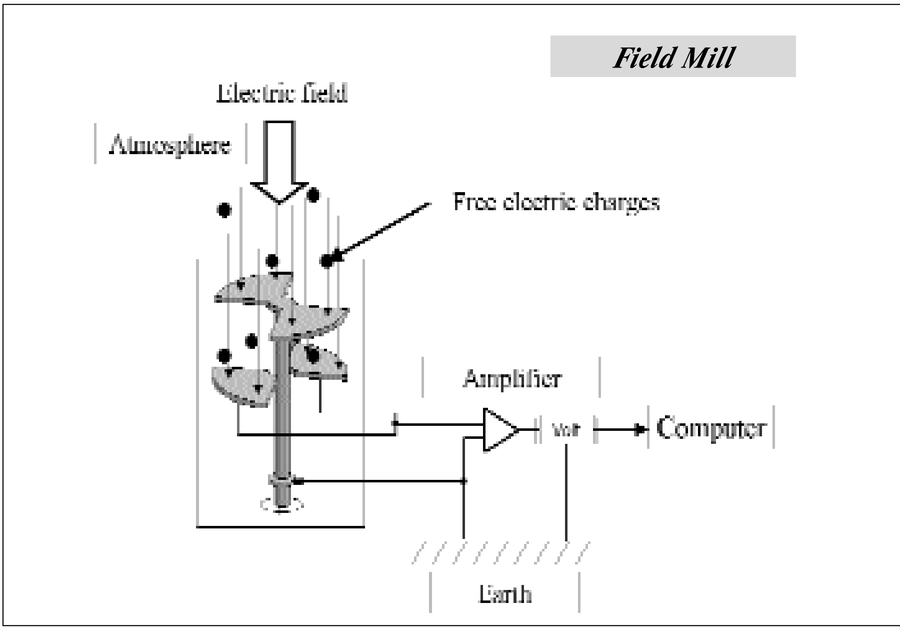

Figure 1. Simplified scheme of the field mill. Two identical butterfly wing-shaped conductors are used. One is fixed and is called the stator, the other, the rotor, is rotating on a vertical axis and it is periodically shielding the stator. The Earth electric field drives free charges toward the mill caught by the stator when the rotor is not shielding it. This produces a periodical current that is amplified and recorded by a computer. The amplitude of the detected current is proportional to the Earth electrical field intensity.

over a geographical point (Doviak & Zrnic 1993). Horizontal resolution for VMI measurements is higher than 500 m, but to be conservative, that upper limit has been used as uncertainty factor for storm positioning purposes. During a stormy day, a radar scan is performed every 10 minutes which equals uncertainty on time. The VMI allows to follow the storm evolution and their position relative to the field mill.

Results

1. 17 July 2003, stormy day. The weather over the Friulian plain, on 17 July 2003, was that of a typical summer stormy day. In the morning fair weather conditions were present and, in the early afternoon, several thunderstorms started developing and evolved following the average synoptic currents. Some of these storms passed far away from the field mill, but one of them crossed over it. Figure 3 reports the whole day Earth electric field registration. The first part presents fair weather values of about 100 Vm^{-1}, from 15:00 UTC to 22:00 UTC there were large variations due to storms and in the late evening fair weather behavior again.

In fair weather conditions the field was almost constant and the signal was characterized by small variations comparable with the measurement error. Some isolated spikes were present, and this was not completely clear, in fact the periodicals checks and calibrations performed on the field meter did not reveal any problem on the apparatus. It is difficult to account for them based on the atmosphere and the boundary conditions only. So far, isolated spikes are supposed to be sporadic erroneous outputs produced by the sampling interface between the instrument and the personal computer. This is common to other meteorological instruments operated at a high sampling frequency. The action of the storms on the field started with a gradual increase since 14:00 UTC (Figure 4). In this case, no thunderstorms were close to the field meter, but they were more than 20 km northwards. Storms raised the intensity of the field to about 500 Vm^{-1} pointing downwards. After 15:00 UTC, when the storms moved eastwards along the main synoptic flow and their distance from the instrument was about 30 km, the field weakened reaching almost fair weather values. The number of cloud to ground lightning strikes associated with these storms was quite large, about one strike per minute, but the strikes did not produce any significant variation on the recorded field. At 15:40 a small convective cell developed close to the measurement site, about 5 km southeast; this is clearly reported in Figure 4 in which the average VMI over the area 10’x10’ increases but the VMI aloft

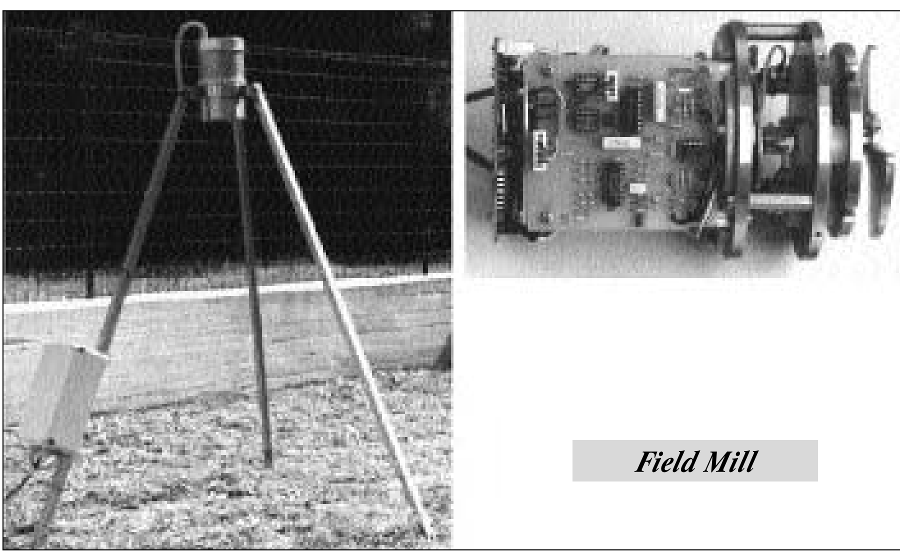

Figure 2. Pictures of the field mill. The mill is placed at 1 m above the ground and it is connected to a personal computer for ongoing data storage. Signals are sent to the computer through a coaxial wire.

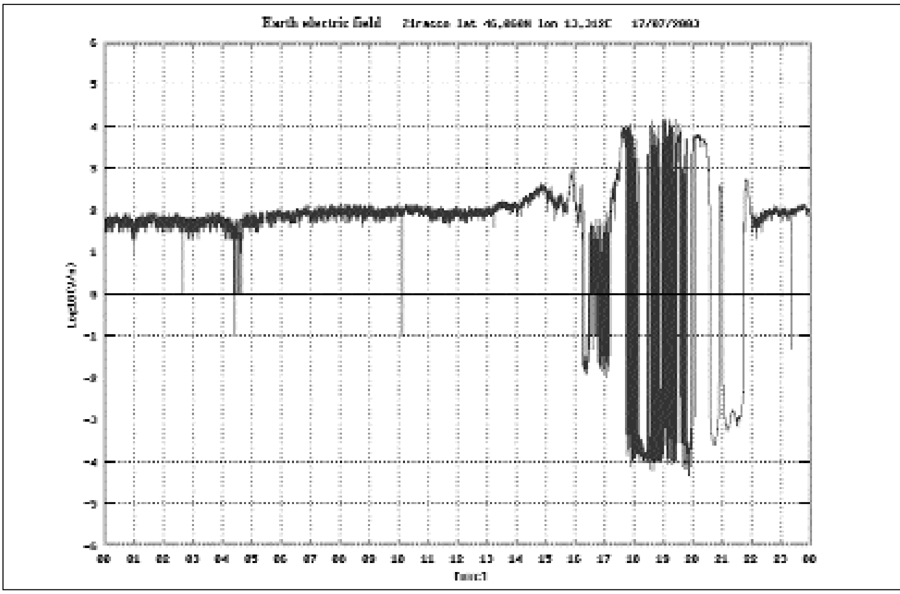

Figure 3. Time series of the Earth electric field recorded at Ziracco on 17 July 2003. Time in UTC hours is reported along the abscissa while electric field intensity in Vm^{-1} is plotted using a logarithmic scale along the ordinates. Positive values of the record refer to the downward field, while the upward pointing field is negative.

the measurement site is negligible. In this situation, the Earth electric field strengthened up to 10^3 Vm^{-1} following the increasing trend of the VMI average intensity and then decreased when the storm weakened (16:00 UTC). No significant lightning activity was associated to that storm. After 16:20 UTC several short lived small storms started forming in the area at a distance greater than 10 km from the field meter. The Earth electric field presented a long-term oscillation from downward to upward direction with an amplitude comparable to fair weather intensity. This oscillation is very similar to that characterizing the end of the storms, usually referred as the end of storm oscillation (EOSO). However, in this case it was not possible to provide a straightforward interpretation because of the complex convective situation surrounding the field meter. In Figures 4 and 5, it is interesting to note that, from 16:30 UTC to 17:00 UTC, the lightning activity significantly increased and several sharp field inversions were superimposed to the long-term oscillation. Those sharp inversions are associated with the lightning sudden discharging action and they are visible in Figure 4, but not in Figure 5 where a 1 minute moving average filtering action is applied to the time series. At 17:00 UTC, a well-structured and developed thunderstorm, likely a supercell, was about 30 km northwest from

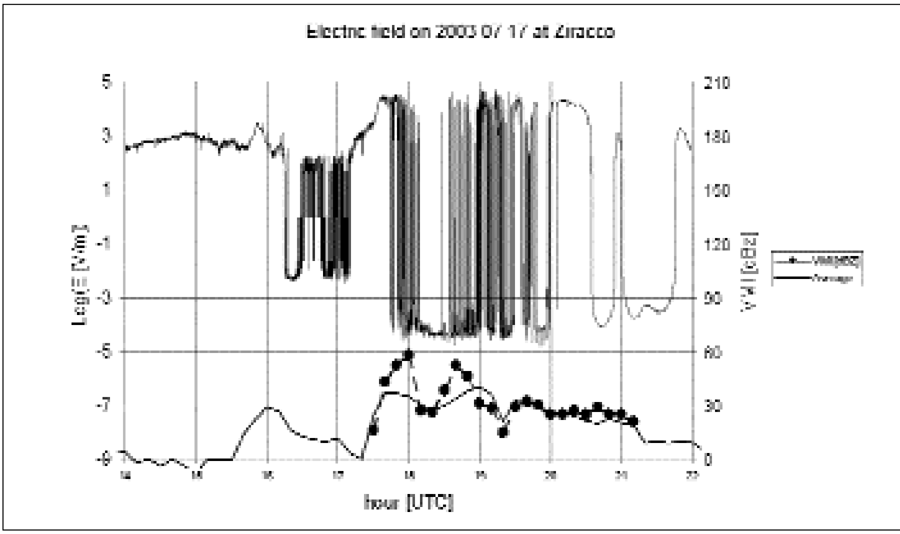

Figure 4. The stormy part of the Earth electric field recorded at Ziracco on 17 July 2003 (solid line on the upper side of the plot). Field intensity and VMI radar reflectivity are plotted versus UTC time. VMI information is reported: the VMI value exactly above the field mill (solid line with dots) and the average VMI computed over an area of 10'x10' (about 250 km^2) centered on the field mill position (solid line in the bottom of the plot). For each time, all VMI records refer to the weather situation present during the previous 10 minutes. The electric field is set positive when it is pointing downward and it is reported in black.

the instrument, it moved towards the measurement site and it increased in size. The electric field stopped the long-term oscillation and pointed downward intensifying up to 20 kVm^{-1} in less than 30 minutes. The maximum field intensity was associated with the maximum VMI value aloft the instrument, which means that in those minutes the storm was very active over the measurements site (Figure 4). The lightning activity increased and the field experienced again sudden inversions with amplitudes of kilovolts. These features can be seen in Figure 6 showing a zoom of the time series over the lightning-affected region. At 18:10 UTC the storm weakened and moved eastward and the field was strong – greater than10 kVm^{-1} – but pointing upwards without any lightning inversion even if the lightning activity in the surroundings continued to be high (Figure 5). Those lightning strikes were mainly due to a new storm approaching the measurement site from west but it passed about ten kilometers south to the field mill. The field was still strong, upward pointing and rich of lightning signals. After 20:00 UTC all storms were farther 20 km from the field meter, and following an EOSO shape the electric field converged towards fair weather values.

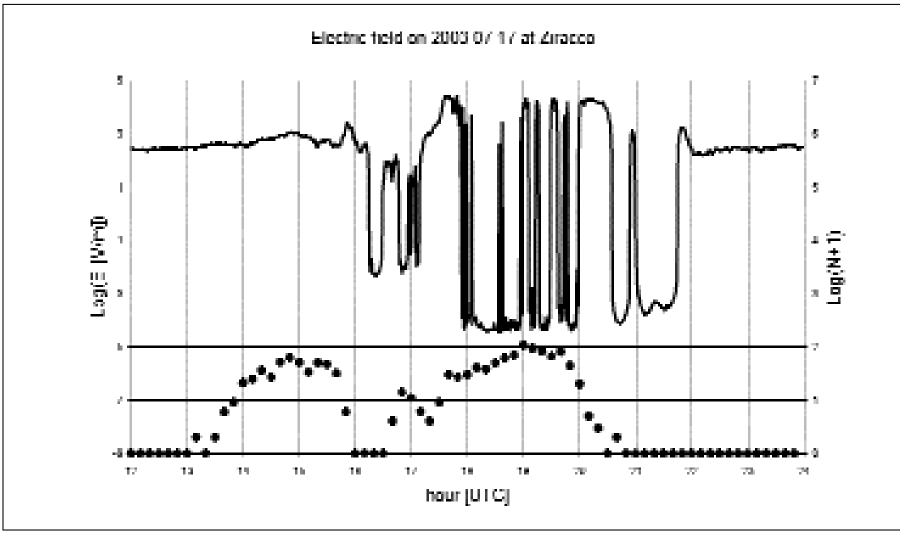

Figure 5. The stormy part of the Earth electric field recorded at Ziracco on 17 July 2003. The moving average over one minute of the electric field intensity has been plotted (solid line). The number of lightning strikes clustered every ten minutes over an area of 2° x 2° (about 35,000 km^2) centered on the field mill position are reported as dots. The electric field is set positive when it is pointing downward and it is reported in black.

2. The end of storm oscillation. Some aspects of the electric field evolution described in the previous section are amenable to a simple model of thundercloud electric charge distribution. Since the first experiments and observations of Wilson (1920), the charge distribution of thunderclouds was schematically represented as an electric tripole (Figure 7). That model assumes that electrical charges are distributed almost horizontally across three main layers (Byrne et al. 1983): the lower positive one, storing some Coulombs of positive ions and usually close to the cloud bottom; the main negative layer, placed above the lower positive one and storing several tens up to about one hundred of Coulombs of negative charges; the main positive layer, above the main negative one, which is close to the cloud top, storing an amount of positive charges comparable with that present in the main negative layer. That stack of layers represents an electric tripole with a vertically oriented axis. Of course, in many experiments, reality was found to be significantly different from that depicted by the tripole model (Rust & Marshall 1996), but the tripole model seems to be sufficiently reliable to document the ground EOSO behavior of the electric field, at least qualitatively. According to tripole model, the EOSO phase is the result of the storm motion. In fact, the total field generated

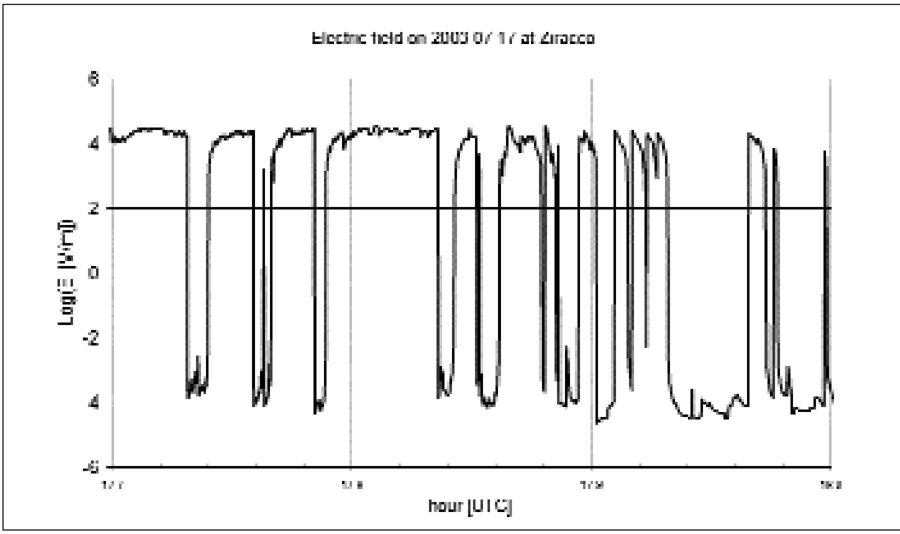

Figure 6. Zoom of the Earth electric field reported in figure 4. This part of the time series is dominated by the lightning discharges, which produce sudden inversions of the field with amplitudes of several kilovolts. The non-symmetric shape of the inversions is evident. In fact, each inversion has a sudden inversion followed by a slower recovery of the original field. The pattern is very similar to that of a capacitor that is discharged and then recharged.

by the tripole is the sum of the contribution of each charged layer. Because of their different sign, intensity and vertical position, at the ground this sum results in a typical radial wavy variation of the electric field in space, moving away from the tripole axis. Of course, the same is true if the storm is moving and the field is measured in the same position. So the last part of the record in Figure 4 is interpreted as the combination of the EOSO of the storms that are moving away from the instrument.

3. The recovery curves of lightning strikes. When a lightning strike occurs, a considerable amount of electric charge in the cloud is neutralized. In the simple tripole model, this results in the variations of the tripole characteristics and consequently in the field that it produces. Different types of lightning discharges are possible: intracloud discharges or cloud to ground discharges. Usually intracloud lightning strikes are much more frequent that cloud to ground ones (Rakov & Uman 2003). In the section of record presented in Figure 6 it is not possible to recognize which kind of lightning strike occurred. Anyway, a general behavior of the field can be identified when a discharge occurs: there is a sudden drop of the field and a subsequent recovery of the original field value in a period ranging from some seconds to one or

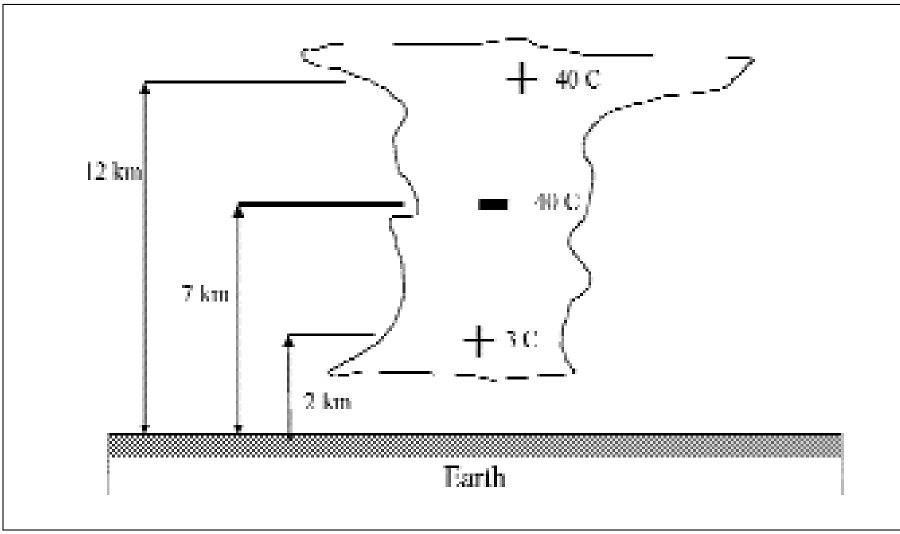

Figure 7. An idealized scheme of the electric charge distribution in a thundercloud according to the tripole model. Charge values and heights are roughly indicative of real values and they attempt to summarize the average situation reported by the various in situ measurements available in literature. Charge values are reported inside the cloud and they are expressed in Coulomb.

two minutes. Not all recovery curves have the same shape, some of them present a linear trend, others are close to an exponential law. The recovery curves depend on the electrification mechanism acting on the cloud and they could be affected also by the corona phenomena at the ground. When the Earth electric field reaches values larger than 5-6 kVm^{-1} (Standler & Winn 1979) pointed bodies present at the ground are suitable for ionization and the production of positive ions in their surrounding is called corona effect. The positive charges produced by corona effect are supposed to play an important role in the recharge process after a lightning discharge (Kamra & Pawar 2002). On the other hand, the physical mechanisms responsible for cloud electrification are not well-defined and the suggested and tested hypotheses are not completely exhaustive. Even if the differences observed in the recovery curves could be the result of the corona effect, there was not a clear separation between the shape of the recorded curves when the average electric field was larger than 5-6 kVm^{-1} and that of the curves revealed in weaker field. Furthermore, several of them are very likely superimposed.

Discussion. The measurements of the Earth electric field, made at the ground by means of the field mill here described, show that the instrument reveals the presence of a storm at a distance closer than about 30 km, even in case of significant thunderstorms with lightning strikes. In case of convective clouds developing in the area in which the instrument is sensitive, or in case of well-developed storms entering that area, it is possible to recognize the event about 20-30 minutes ahead its maximum because of the large increase of the field intensity. Generally, no lightning strikes are observed close to the field meter at distances less than 5 km, if the field intensity is less than 5-10 kVm^{-1}. This feature suggests that the instrument could be used for practical purposes in which it is necessary to recognize the occurrence of the environment prone to lightning discharges. Unfortunately, this is not sufficient for weather forecasting purposes because of the very short time available from the electric field rise and the occurrence of thunderstorm related phenomena such as rainfall, hailfall and strong wind. Based on these results, it is likely that a network of field meters with a mesh size of about 20-25 km could monitor the Earth electric activity at the ground and could be used for practical applications. From a purely technical research point of view, this paper points out the complexity of the interpretation of Earth electric field measurement at the ground. Fair weather measurements support the existence of a global electric circuit that maintains the vertical potential gradient and its average value at the ground is comparable to those revealed in other sides all over the world (about 100 Vm^{-1}). Measurements in stormy conditions suggest that the electrification of a convective cloud is produced by means of quite a fast mechanism that takes about half an hour and it is maintained very efficiently also during the mature phase of the storm. In fact, lightning strikes produce a sudden removal of electric charges, but the electrification mechanism restores the electric charge excess in seconds or at least in a few minutes. The recovery curves of the field after a discharge show different behaviors, and this suggests that the electrification mechanism is very probably the result of various contributions. The analysis here presented has offered a quantitative view of the Earth electric field and a qualitative interpretation of the results. Future developments of this work are planned and they are going to include the best fit of the tripole model parameters on the observed data for several stormy cases, quantitative correlation between full radar variables and the field intensity and specific studies on a single recovery curve shape.

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