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Electrical Environment in a Storm Cloud

This article gives an overview of the electrical characteristics of the thundercloud and the predominant mechanisms that are at the origin. The specific cloud that can produce lightning is described and the parameters that control its development and its organization are discussed. According to the variety of the scales of time and space associated with the mechanisms that occur within the thundercloud, it is difficult to simulate them both experimentally and numerically. Thus, the advances in the knowledge of the thunderstorm electricity have been sometimes relatively slow and have raised a lot of debates. Furthermore, in-situ observation remains difficult because of the hostility of the thundercloud medium for instrumentation, sensors, aircraft or other carriers of sensors. The responses to the questions in the domain of thundercloud electricity can sometimes remain speculative. However, recent detection techniques and laboratory experiments allow a better knowledge of the cloud electrical environment to be obtained. All aspects about lightning flashes and electrical discharges will be covered by other contributions in this issue.

History of the thundercloud electrical description

For most researchers, meteorologists and official organizations, lightning and thunderstorms are completely interdependent. Since the time of Benjamin Franklin, during the eighteenth century, it has been understood that the lightning flash is of electrical nature and therefore the thunderstorm that produces it is the seat of electrical processes. The first experiments simply showed that negative charge was present within thunderclouds and especially in their lower part. The difficulty in making in-situ observations has differed the understanding of the nature and causes of thundercloud electrification. Later, at the beginning of the twentieth century, C.T.R. Wilson, a famous scientist known for the Wilson cloud chamber used to follow trajectories of ionizing particles, showed that the thundercloud could hold both signs of charge by performing measurements with new sensors on the ground [1]. The charge structure as a positive dipole (positive charge above negative) of the storm was pointed out. However, all thunderclouds did not correspond with this scheme and reverse structures were sometimes observed from in-situ measurements [2]; [3]. In the second half of the last century, a lot of theories of charging have been proposed, along with some experiments of cloud exploration with new sensors using modern electronics and carried by aircraft or balloons. In parallel, laboratory experiments have simulated cloud microphysics and charge separation at small scale between particles. Resulting from these advances, the question of the effective contribution of the charging processes to the cloud electrification has fed a lot of discussions between researchers in the community of atmospheric electricity [4]; [5].

To return to the electrical cloud structure, a third and smaller charge center was also observed within many storms [6]. Charge was also observed at the periphery of the cloud as screening layers, especially at the cloud top [7]; [8], which was also confirmed theoretically. Finally, more complex charge structures have been observed with repeated experiments of cloud soundings and techniques derived from lightning mapping, or obtained with electrified cloud modeling (see in the following). This paper reviews current knowledge in the electrical characteristics of thunderclouds. The first section describes the thermodynamics and the microphysics of different categories of storms. The second section is devoted to the charging processes that can take part within the thundercloud electrification. The third section describes the main electrostatic structures observed or simulated within thunderclouds.

Thundercloud development and organization

Thunderclouds are the result of air convection combined with substantial humidity. The convection can initiate when conditional instability is released. In order to describe the conditional instability, the parcel theory is used: when a parcel of air moves in an upward vertical direction, it follows an adiabatic process – no energy is exchanged between the parcel and the surrounding air – which reduces its temperature at a rate of about 10°C every kilometer. If the parcel is found to be less cold than the surrounding air at its new altitude, it can continue to rise because of an upward buoyancy force. Furthermore, if the parcel air saturates during its ascent, its temperature decreases more slowly because of the latent heat of condensation released. Under these conditions, the vertical motion of saturated air is called 'moist convection' and it happens on a large scale within the thundercloud. Thus, chances for moist convection are determined by the amount of moisture and high temperature in the lowest kilometers of the atmosphere, together with a strong decrease of temperature with height (colder air above) in the 2-5km layer. Additionally, if atmospheric circulations are present, they can adiabatically cool down (by lifting) mid-level layers and force parcels from lower levels to ascend, so that they become warmer than their surrounding air and will continue to rise by themselves (after having reached the Level of Free Convection). The atmosphere capability to produce 'buoyancy' can be expressed thanks to criteria, for example, the Convective Available Potential Energy (CAPE), which is a potential energy in J kg^{-1}:

$$CAPE = \int_{LFC}^{EL} g\left(\frac{T_v^{parcel} - T_v}{T_v}\right) dz$$

Where EL and LFC are the equilibrium and free convection levels, respectively; i.e. the heights between which a parcel is warmer than its surrounding air. T_v indicates the virtual temperature (temperature corrected for moisture content, so that densities can be compared). Figure 1 illustrates the calculation of this criterion. CAPE can be converted to kinetic energy in the form of a convective updraft, the velocity w of which is generally proportional to the square root of the CAPE:

$$w = \sqrt{2 \cdot CAPE}$$

However, on one hand, precipitation can prevent the calculated upward velocities from being attained and, on the other hand, other factors such as wind shear interactions with the updraft can increase the strength of wide updrafts. Also, CAPE in a certain area will eventually be consumed if released because, in effect, the troposphere is mixed towards a neutral thermal stratification. Thus, thunderstorm activity may last longer in areas with steeper lapse rates and higher CAPE.

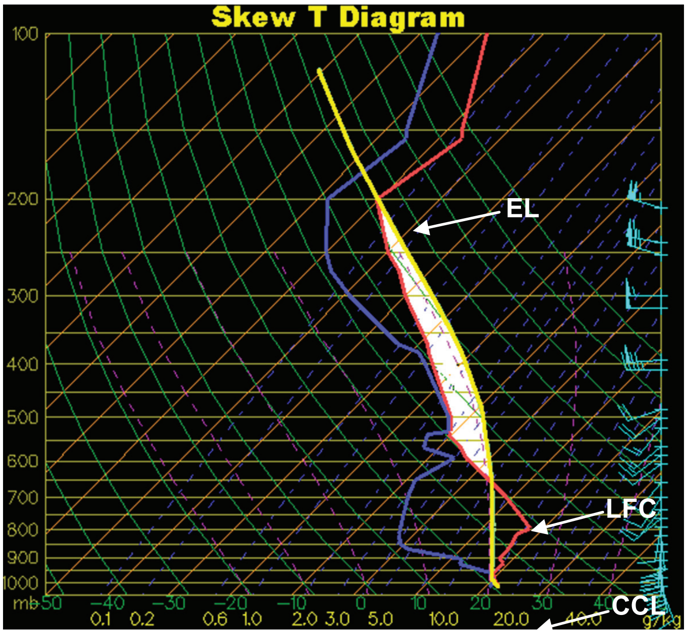

Figure 1 - CAPE from a skew-T thermodynamic diagram: the white shaded region on the sounding below is the CAPE area. The red line is the atmosphere sounding and the thick yellow vertical line is the parcel sounding. CAPE is especially important when air parcels are able to reach the (LFC) or Layer of Free Convection. The white region ("positive energy" region) is called CAPE and is expressed in Joules/kg. A CAPE value more concentrated in the lower half will produce a stronger updraft than an equal CAPE value that is stretched higher and narrower.

The thundercell is the basic organizational structure of all thunderstorms, as previously depicted by Byers and Braham [9] and this notion became the fundamental paradigm for thunderstorms. A typical cell lives for about 15-60 minutes, including the three stages illustrated in figure 2: growth stage as towering cumulus, mature stage with both updraft and downdraft, and dissipation as cool outflow cuts off the base of the updraft from its supply of warm air. At its mature stage, it consists of an updraft, where warm moist air rises and water vapor condenses into cloud particles from which precipitation-sized particles may grow; and a downdraft, where precipitation falls and drags the surrounding air downward, helped by evaporative cooling of cloud and precipitation particles near the top and sides of the cloud. The interaction of vertical wind shear with buoyant bubbles is responsible for enhancing updraft and downdraft velocities, which has a consequence on the longevity of the convective cell.

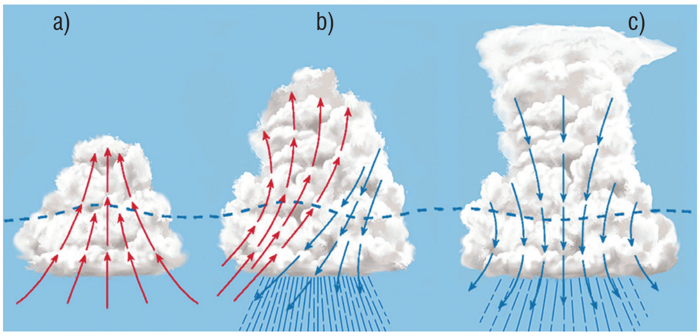

Figure 2 - The thundercell at different stages of its lifetime: a) development stage, when only updrafts are generated; b) mature stage, when updrafts and downdrafts coexist; c) dissipating stage, when only downdrafts subsist.

In the cases of strong vertical shear (>15 m/s shear vector between 0-6 km altitude) and clockwise turning of layer shear vectors at heights within the lower kilometers, a storm cell may acquire rotation as it ingests vorticity via the winds that it ingests. These special cases of cells are called 'supercells' and typically produce large hail (2-6 cm or even larger) as evidence of their exceptional updraft strength, as well as tornadoes and downbursts of damaging winds (figure 3a). As proposed by Browning [10], the supercell model initially was conceived as a quasi-steady form of an ordinary cell. Browning [11] later developed a new definition of a supercell, as a convective storm having a mesocyclonic circulation. The mesocyclone creates the radar reflectivity morphology ("distinctive" features [12], such as hook echo structures and Line Echo Wave Patterns (LEWPs)) typically associated with supercells (figure 3b). Thus, supercells can have strong updrafts, even when the static instability, as measured by CAPE, is modest [13]. Because the mass continuity requires compensating subsidence around the updraft and the convective downdrafts typically do not process as much mass as the updrafts [14], the most intense updrafts will virtually always be isolated. Thus, supercells are relatively rare as well as isolated storms, and are predominantly a mid-latitude phenomenon. Tropical environments usually do not have adequate shear to develop deep, persistent convective mesocyclones [15].

Figure 3a - Picture of a supercell.

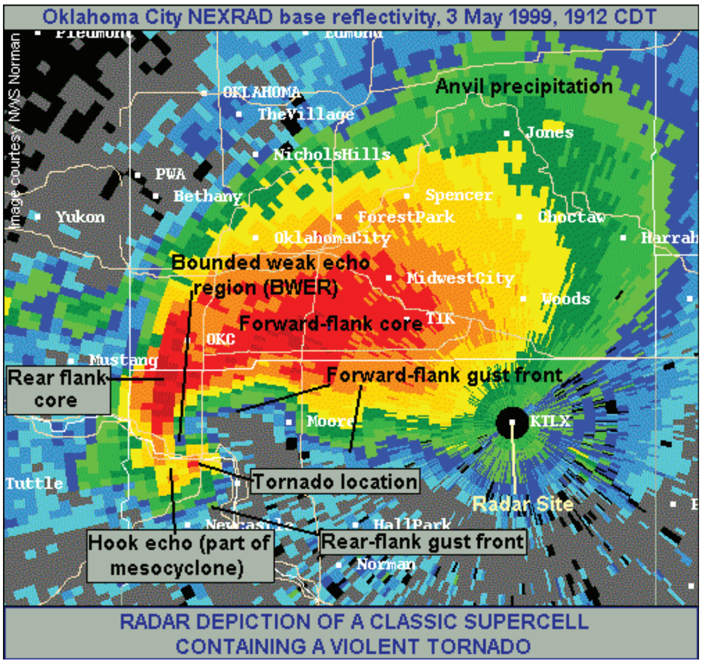

Figure 3b - A radar image of a violently tornadic classic supercell near Oklahoma City, Oklahoma, USA on the 3rd of May 1999. (http://www.spc.noaa.gov/faq/tornado/radscel.htm)

A multicellular thunderstorm cluster is a thunderstorm that is composed of multiple cells, each at a different stage in the life cycle of a thunderstorm [16]. These old cells dissipate as new cells form and continue the life of the thunderstorm system, with each cell taking a turn as the dominant cell in the group. New cells usually form in the upwind (usually western or southwestern) part of the storm, mature cells are usually in the center of the storm and dissipating cells are usually in the downwind (usually eastern or northeastern) part of the storm. The picture in figure 4 illustrates such organization of cells. The multicellular storm cluster can last for hours, while each individual cell should only last for about 20 minutes. These storms can sometimes be severe and sometimes have awkward paths due to the thunderstorm sometimes not following the path of the cells that compose it. Any severe activity in one of these storms will most likely come from the dominant cell near or after its peak updraft strength.

Figure 4 - A multicell cluster consists of a group of cells at different stages of the life cycle, moving as a single unit. New cells tend to form along the upwind and individual cells take turns at being the most dominant. (© Harald Edens).

Figure 5 - Picture of a squall line (© Oscar van der Velde). A squall line is a line of severe thunderstorms containing heavy precipitation, hail, frequent

Linear organization is often observed in the convective systems. As a matter of fact, since outflow is an effective mechanism for lifting near-surface parcels to their LFCs, it can have a dominant role in the development of subsequent cells when it develops. If the horizontal convergence along outflow boundaries has a value of 10^{-2} s^{-1} through a layer as deep as one km, the resulting upward motions at a height of one km are of an order of 10 ms^{-1}, which can initiate deep convection [15]. As convection continues, new outflows merge with old ones, resulting in an expanding pool of cold, stable air at low levels, often with new convection on its leading edge, as the outflow pushes into untapped, potentially buoyant air ahead of the outflow. Such systems are organized linearly and include mesoscale convective systems (MCSs), such as for example squall lines (figure 5). A related factor in developing a linear structure is the nature of the process responsible for the first convective cell initiation. When the lifting mechanism is a front, a dryline, or a pre-frontal trough, there are along-line variations in the lift resulting from these processes. Also, there is variability in the thermodynamic characteristics of the lifted air. Thus, the first convective developments can occur separately to form individual cells but rapidly, convective elements develop along the line and merge because of the overall linear nature of the initiating mechanism for thunderstorms. The subsequent development of cold outflows serves to reinforce this evolution; hence, the high frequency of this sort of organization to convective systems.

The electrification processes

One of the longest-standing questions is how convective clouds become electrified in order to produce lightning. To answer this question, researchers have performed laboratory experiments and field observations, but it is difficult to obtain a definitive explanation because of the range of the distance scale between the microscale of the physical processes concerning the cloud hydrometeors (water particles) and the size of the thundercloud for the charge structure. Likewise, the multiple processes taking part in the charge and discharge phenomena within the thundercloud cover a very large range of time. Furthermore, it is very difficult to make *in situ* measurements, because the storm conditions are hostile to the instrumentation. Some mechanisms are described here that can take part in the cloud electrification, either as a process to initiate and sustain it, or as complementary processes to reinforce it.

Non-inductive ice-ice charging mechanism

Of all charging mechanisms proposed during past century, the one considered as the best able to start the electrification within the cloud and to reproduce the vertical charge layering and the amount of charge observed, involves rebounding collisions between ice crystals and graupel pellets. The graupel pellets can be described as small porous hail and grow as small supercooled cloud droplets freeze to their surface (riming). This mechanism is non-inductive, i.e., it does not need an external electric field to create charge on a particle. To study this kind of mechanism, researchers use laboratory experiments to empirically analyze the different aspects of the electrical properties of particles in a controlled environment that can reproduce that of the thundercloud. Early on in these experiments, it was found that the result of the mechanism strongly depends on several parameters. Takahashi [5] showed that according to the ambient temperature and the liquid water content, riming particles charged positively (for higher temperatures and for either very high or low cloud water content), or negatively (for colder temperatures and for the mid-range of cloud liquid water content). Similar experiments performed by a University of Manchester (UMIST) group led to slightly different results: there indeed was a charge reversal temperature below which the riming particle acquires negative charge, but this temperature decreased in their case as effective cloud water content increased, meaning that positive charging becomes more likely [17], [18], [19]. The largest difference was a reversed polarity for the riming particle at low effective water content, negative for Takahashi's results [5] and positive for [18]. Both results are shown in figure 6. It was found that the charge amount transferred during a collision depends on the size of the ice crystal [20] and that for a large amount of liquid water content, the droplet size distribution can modify the sign of the charge of the riming particle [21]. Recently, researchers from Argentina [22] obtained results that show that at a temperature > -19°C, the magnitude of the charge transferred decreases as the liquid water content increases.

The experimental setups can be a major cause of the different laboratory results. For example, the use of a single cloud of water and ice particles (UMIST experiment), instead of mixing two separate clouds of water and ice particles shortly before encountering the riming

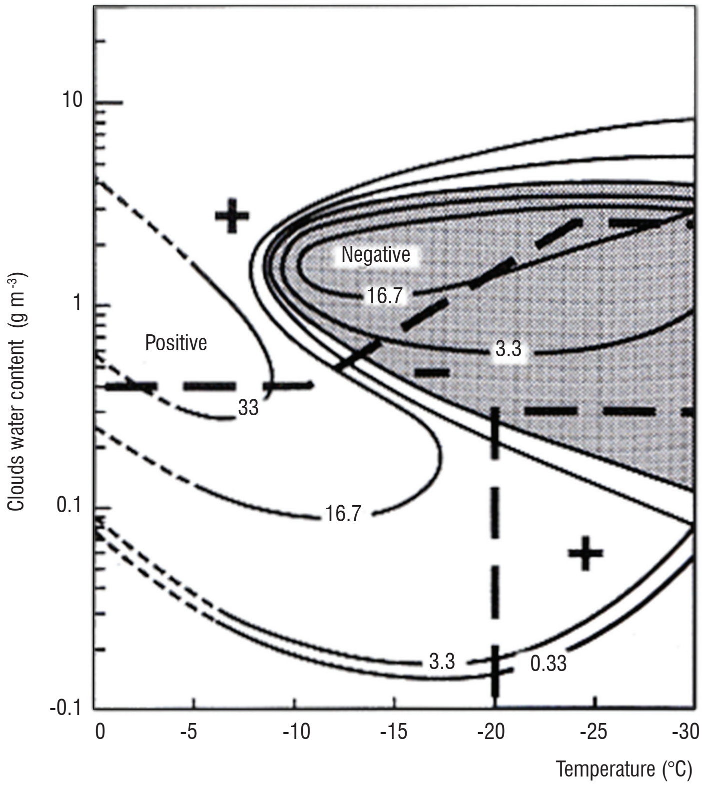

Figure 6 - Polarity of charge gained by rimed graupel after a collision with an ice crystal, as a function of ambient temperature and liquid water content for the Takahashi [5] experiment (curves) and for the Saunders et al. [18] experiment (lines). The dashed bold lines outline the temperature and liquid water content values at which the charge of the graupel changes its polarity. (From MacGorman and Rust [30]).

target, small ice particles grow at the cost of cloud droplets and the saturation (relative humidity) will be smaller with respect to liquid water ([23], [24]. Lower relative humidity at temperatures around -15°C means higher saturation with respect to ice than to water, which leads to the depletion of vapor from liquid surfaces to ice and a more neutral to positive charge on the riming target [25]. Concentrations of different aerosols, which influence the formation of cloud droplets, may also affect the resulting charge for a given temperature-humidity regime. For example, aerosols can lead to charge reversal, by suppressing the precipitation in the cloud and leaving a greater amount of supercooled cloud water at greater heights and lower temperature [26]. At a large scale, cloud condensation nuclei (CCN) aerosol particles could play a significant role in differences in lightning production between maritime and continental thunderstorms, but no observational evidence could be obtained because of the associated thermodynamic differences. Yuan et al. [27] showed lightning enhancement in the presence of increased aerosol produced by volcanic activity, while the meteorology conditions did not change.

A possible explanation for the difference of the charge polarity on the graupel pellet is given by the laboratory experiments performed by Baker et al. [28] and later by Emersic and Saunders [29]. They found that the target simulating the ice particle involved in the collision with ice crystals was positively charged when its surface was growing more rapidly from the vapor than from the ice crystals, and negatively in the opposite case. However, for the same growth regime of the ice particle, all experiments do not provide the same result and the question is still open even after several series of experiments. Actually, one set of experiments showed that the individual charge gained by a rimed graupel could be either positive or negative [21], and others, while most previous experiments considered the average charge. Despite a lot of questions for this non-inductive mechanism, some agreements can be noted about its contribution to the thundercloud charge, as indicated by MacGorman and Rust [38]: the simultaneous presence of riming larger ice particles and at least a small amount of liquid water is required; For large amounts of liquid water content, the graupel is positively charged and for intermediate amounts it is negatively charged, which explains the main negative charge pole within the cloud; If the temperature is less cold (near zero) the graupel becomes positive, regardless of the liquid water content. Finally, the non-inductive ice-ice charging mechanism matches well with the overall tripole-charge structure often observed. The role of graupel particles in the charging processes is confirmed with in-situ observations, especially when the total lightning activity is detected and the microphysics species are inferred from radar observations (see for example [31]).

Inductive charging mechanisms

All mechanisms of this category cannot explain the charge to produce the primary electrostatic field within the thundercloud. Ion capture is one of the earliest to be suggested, especially by Wilson [1]. It works between ions and falling frozen or liquid hydrometeors in the presence of an electric field, which makes the particle polarized (figure 7a). The ions involved in the process could be mainly produced by lightning flashes [32]. The precipitating particle captures the ions with polarity opposite to the charge of its bottom and repels the ions with the same polarity. Thus, if the direction of the electrostatic field is downward within the cloud, negative ions are captured by the hydrometeor, which becomes charged negatively. The motion of the ions can be driven either by the electric forces, or by the updrafts. The efficiency of the mechanism is related to the relative velocities of both ion and particle. For example, if the particle velocity is low, ions repelled by the bottom of the hydrometeor can be attracted by its top and finally captured, which reduces the efficiency. The capture of charge by the bottom causes a migration of an opposite charge from the top, which reduces the capability for attracting additional charge. The magnitude of the ambient electrostatic field is therefore an important parameter to sustain the mechanism, which does not assign a major role in the primary cloud electrification. For a normal dipole structure (positive charge above negative charge) ion capture tends to transfer a negative charge to the precipitating particles between both poles, which increases the negative charge of the main pole. Ion capture is selective in the presence of an electric field, but it can work for both ion polarities in its absence. If one of the charged ions is predominant, as for example below the thundercloud, the particles can acquire charge by this process.

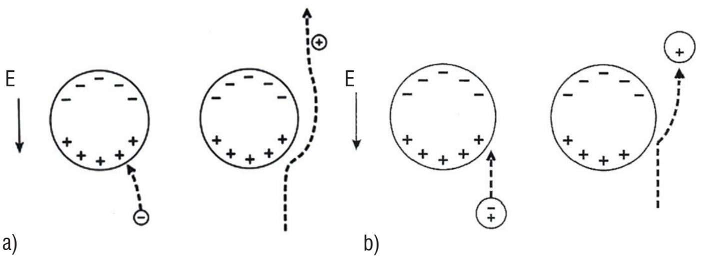

Figure 7 - a) Selective ion capture by a polarized drop. The lower side of the drop attracts the negative ion and repels the positive ion. b) Inductive charging of the rebounding polarized drop and droplet. E is the electrostatic field. From MacGorman and Rust [30].

Another inductive charging mechanism can work between colliding and rebounding particles. If particles have different vertical velocities, the collision between them can occur as described in figure 7b. Particles of different sizes, including precipitating particles and cloud droplets, can be actors of this mechanism. In the presence of an electric field, both particles are polarized and they collide by their bottom for the larger one and the top for the smaller one, i.e., by their oppositely charged sides. After rebounding, both particles carry a net charge, negative for the precipitating one and positive for the one that rises. As for the selective ion capture, this mechanism can reinforce the main negative charge of the cloud.

Other processes

Finally, many other processes were proposed, but it is really difficult to properly estimate their existence under the thundercloud conditions and their relative contribution to the storm electrification. One of these processes is the convective electrification theory, which is completely different from the others, since it does not involve the hydrometeors to create charge within the cloud. It is also called ″Vonnegut convective electrification″ [33] and explains the presence of positive charge at the top of the cloud with the ions entrained by upward air motion. The presence of negative charge at lower levels should be due firstly to being attracted from the cloud environment by the positive charge at upper levels and then carried down by the subsidence. However, quantitative estimations show that the amount of charge and the time delay involved in such a process are not consistent with the observations at the scale of the thundercloud [4], [34], [54]. Ice particles or liquid hydrometeors can gain charge by many other processes, especially during melting for the ice, or evaporation or condensation for the water. Drops can also become charged when they splash. None of these mechanisms can be efficient enough to be taken into account in the storm electrification.

The charge structure of the thundercloud

The tripole vertical structure was proposed early on, but though it is generally well adapted to the thundercell it is not suitable for complex and big storms structures [35]. In a normal storm, negative graupel pellets form the lower of both main poles, while positive lighter ice crystals are advected to greater heights and form the upper pole. A secondary and small positive pole occurs at the cloud base because of the warmer temperatures and possibly because screening layer charge at the bottom of the cloud is ingested.

Normal charge structure

One of these methods involves measuring the electrostatic field (E) within the thundercloud, because it is linked to the overall charge structure and it is difficult to directly measure the charge carried by all types of hydrometeors within the whole thundercloud. Extensive *in situ* measurements of E have been performed with airplanes and balloons, each one providing different characteristics of this parameter. Thus, soundings with balloons provide vertical profiles and airplanes tend to provide horizontal variations at given altitudes. Some measurements have also been made with rockets, with the advantage of obtaining an instantaneous state of the structure. However, most of the works that have been published are based on balloon soundings performed when the thundercloud electrification has been initiated. Thus, the maximum rarely exceeded 200 kV m^{-1}, even though horizontal and vertical components were measured [30]. The vertical soundings of E have been used to infer the charge density in the region crossed by the balloon, thanks to Gauss's law with a one-dimensional approximation [36]. This method allows the net charge to be determined, without identifying the nature of the charge carrier (ions, precipitation, ice particles, etc.).

By using several soundings performed within three different kinds of convective systems (supercell, MCS and mountain storm), Stolzenburg et al. [36] proposed a structure for the convective region of the storm (figure 8). All regions of charge are found to have horizontal dimensions much larger than the vertical ones. The convective updrafts have four charge regions: the lowermost is weak and positive; a main negative charge above this one forms the main dipole with an upper positive charge; a shallow layer of negative charge is added near the upper cloud boundary. Outside this updraft region, six different charge layers are generally observed, with the uppermost still negative and the others with alternating polarity down to the lowermost. However, the latter structure can frequently vary from one storm to another [37].

The altitude of the charge regions within the updrafts change from one convection type to another and the main negative region is related to the average updraft speed. While it can be found at about 9 km in a supercell, it is only at about 7 km in an MCS and about 6 km in a mountain storm. When individual charge measurements were made, the main charge carriers were identified as precipitating particles in the positive lower and the main negative charge regions for the updrafts region, while they corresponded rather with cloud particles above the main negative charge [36], [38], [39]. This kind of structure can evolve into more complex ones after lightning flash production and when the updrafts decline [40]. Generally, intracloud and negative cloud-to-ground flashes are produced from these regions of the storm, the latter requiring intense electrostatic field values at low altitude, generally allowed by the presence of the lower positive charge.

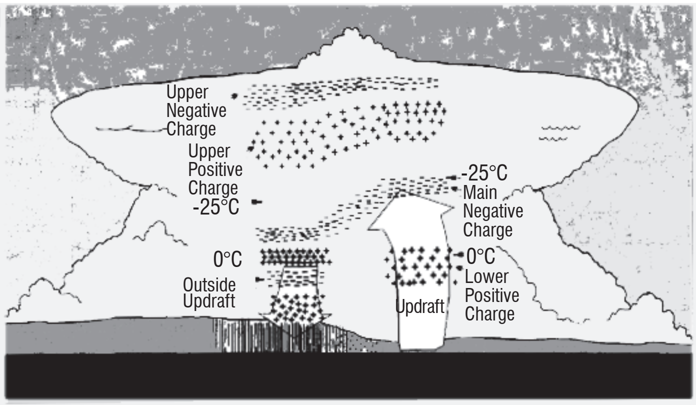

Figure 8 - Charge structure in the updrafts and the downdrafts of a thunderstorm. From Stolzenburg et al., [56].

Large amounts of positive charge have been observed [57] within the stratiform regions associated with the MCSs. According to the long time of activity of a MCS, the charge structure within the stratiform characterized by weak updrafts, a horizontally extended melting region and dying cells, may be complex. Marshall and Rust [57] identified two kinds of structure, one with five vertically-distributed charge regions, sequentially positive and negative, and one with only four regions. The most dense charge region is around the 0°C level in each case and can be positive or negative. Another type of structure, called "anvil-type", is characterized by a cloud base above the melting level, a deep positive charge within the cloud, a lower negative screening layer and a possible upper negative layer. The reservoir of positive charge located at or above the melting level can provide charge for positive flashes with large peak currents and/or large charge moment changes, which are generated close to the convective region and at the origin of sprites [41].

Inverted charge structure

Data from lightning mapping systems displays the path of the flashes, thanks to the VHF radiation produced by their leader phases [42]. In a normal charge structure, intracloud flashes move through two layers of charge: positive charge above negative charge. Because the negative leader radiates more than the positive one, the thunderstorm charge structure can be inferred by examining a composite of the charge structures of many individual flashes within a storm [31]. In specific storm cases, inverted-polarity intracloud flashes move through two layers of charge in the opposite configuration: negative charge above positive charge [43]. Thus, the main dipole exhibits a negative charge above a positive charge [44]. These storms tend to produce predominately positive cloud-to-ground lightning flashes and inverted-polarity intracloud flashes, and they can occur preferentially in some regions as US high plains region[45].

The Severe Thunderstorm Electrification and Precipitation Study (STEPS) took place in the early summer of 2000, in order to study severe storms occurring within this region and to describe their charge structure [44]. Balloon field soundings and data from a lightning mapping array (LMA) were used during the experiment. The LMA stations use a time-of-arrival technique to provide three-dimensional location and time of sources of very high frequency (VHF) radiation pulses produced by the electrical breakdown during the lightning channel propagation [46], [47]. For a lightning flash, the LMA may locate hundreds to thousands of such VHF sources, which allows the lightning path and the total lightning activity to be mapped in detail. Several cases of storm were analyzed with both means of electrical investigation associated with radar observations (see for example [37] for a multicell storm). Four sections of this multicell structure storm were analyzed at different periods of its lifetime. The electrical structures of each of these sections differed from the others during all or part of the analyzed periods.

Figure 9 displays the charge structure provided by the LMA within four regions of the storm system at the first period analyzed. The information is qualitative, since any charge density value may be evaluated and it shows the location of the charge regions. Thus, the regions are also found to have a much greater horizontal extension and the number of regions is comprised between two and four. One section (A) has a normal dipole, while three others display the inverted structure. From the same case study, Weiss et al. [37] made a comparison of both methods (balloon and LMA) of charge structure investigation and the result is displayed in figure 10 for the most complex charge structure found in a convective section of the storm. The same vertical distribution of charged layers is found by both methods, with some differences in the heights. The intracloud lightning flashes concentrated within the regions with large radar reflectivity values and the rate of cloud-to-ground flashes, predominantly positive, increased when reflectivity cores descended to lower heights.

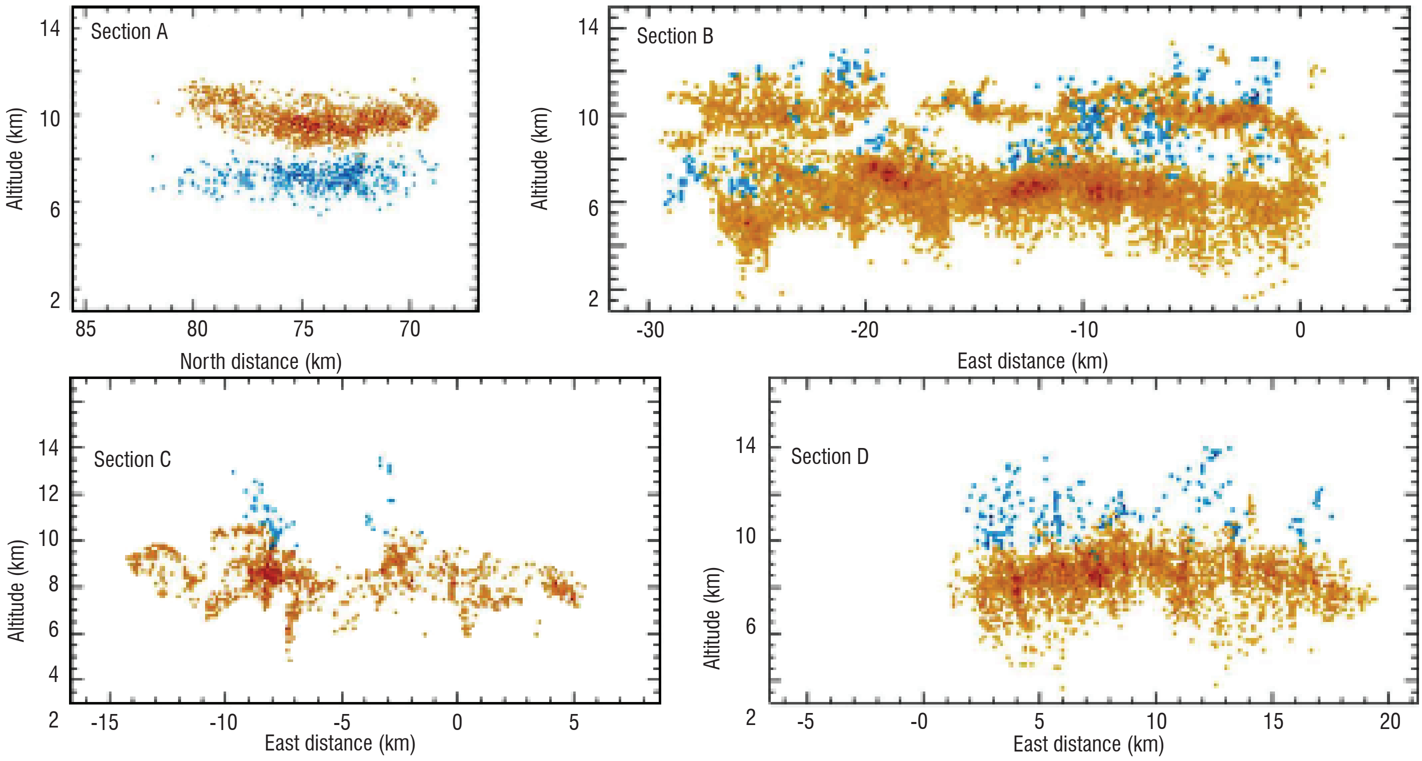

Figure 9 - Density of VHF sources inferred from LMA data and produced by flashes during 10 minutes in four different regions of a storm. Blue indicates negative storm charge and orange indicates positive storm charge. Darker colors represent larger source densities. From Weiss et al. [37].

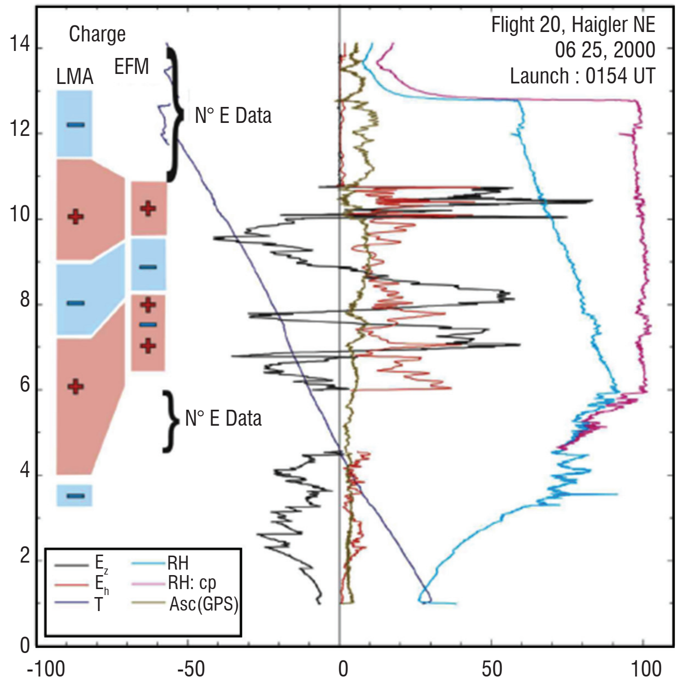

Figure 10 - Comparison of the charge structure (left side) for a storm documented during STEPS with a LMA system and with balloon soundings of electric field and thermodynamic parameters. The negative charge inferred in the EFM data at 7.5 km was likely due to charge deposited by lightning. From Weiss et al. [37].

Simulation of cloud charge structure

Three-dimensional dynamic cloud model incorporating airflow dynamics, microphysics and thunderstorm electrification mechanisms are used to examine the relationships between flash rate and other storm properties [49],[48]. Several parameterizations of the non-inductive charging process are generally used in cloud models and the inductive charging process can be included as well. The electric charges are transported along the airflow by the hydrometeor categories, which are involved in the charging processes. They are exchanged according to the various microphysical mass transfer rates and by assuming some charge–dimension relationships. The electric field is obtained by inverting the Gauss equation. When the electric field locally exceeds a given threshold a lightning flash is triggered and its propagation is driven by the electric field according to the theory of the bi-leader [50]. It propagates in two opposite directions until the magnitude of the electric field falls below a prescribed value. A charge amount is neutralized according to specific parameterizations.

Numerical experiments show different kinds of charge structure with a high sensitivity to the parameterization of the non-inductive charging process [51],[52], [48]. Figure 11 displays the vertical cross sections of the total charge density performed with the Meso-NH model at different stages of the storm documented during STERAO [53]. In this case, a negative dipole was first generated (negative charge above positive charge) and then the structure became more complex, with the normal tripole in the convective regions and a negative screening layer at the top of the cloud. Mansell et al. [48] used a three-dimensional dynamic cloud model and compared five laboratory-based parameterizations of non-inductive graupel-ice charge separation. Three of these schemes produced a normal polarity charge structure, consisting of a main negative charge region with an upper main positive charge region and a lower positive charge region. The other two schemes, which are dependent on the graupel rime accretion rate, tended to produce an initially inverted polarity charge structure and + CG flashes. Figure 12 illustrates the result of two schemes, in terms of charge structure, with a different number of charge regions.

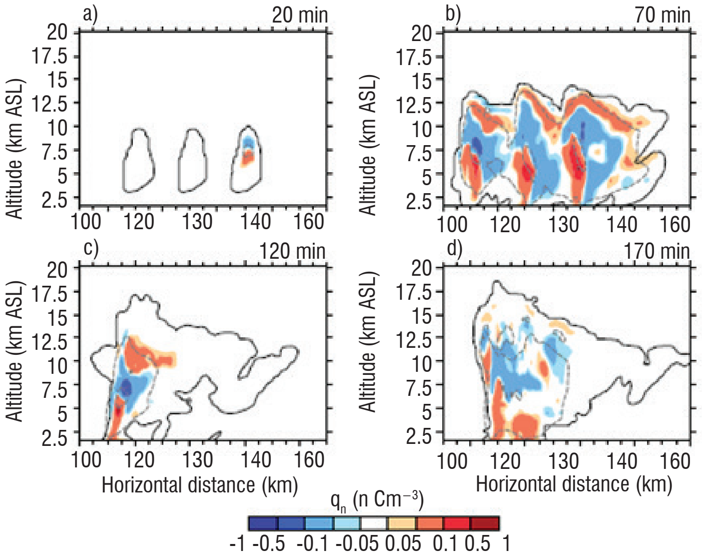

Figure 11 - Simulation of a STERAO case of storm: Vertical cross-sections of the total charge density (colors; in n Cm^{-3}) along (a) 20 min, (b) 70 min, (c) 120 min and (d) 170 min. The black solid line corresponds to the cloud contour. Dashed gray contours show the electric field module (10 and 50 kVm^{-1} contours). From Barthe et al. [53].

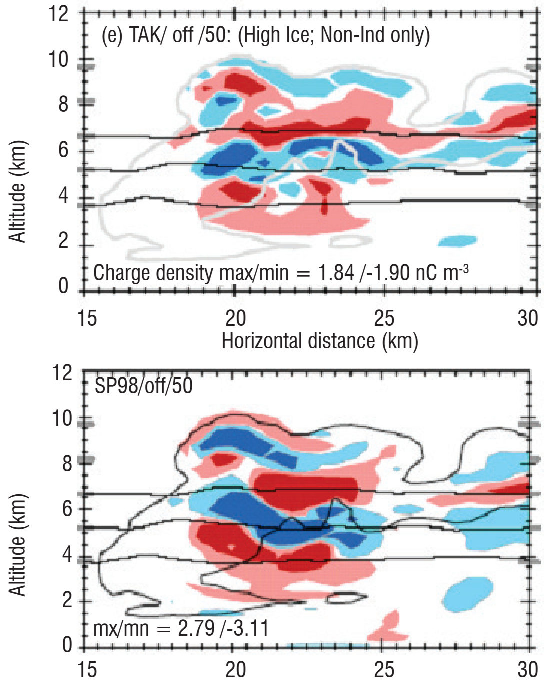

Figure 12. Charge structure of a multicell storm obtained by modeling with two non-inductive charging schemes: upper panel, [5] and lower panel, [19]. Red and blue shading denotes positive and negative charge regions, respectively. From Mansell et al. [48].

Conclusion

Some aspects of thundercloud development and its electrical characteristics have been described in this paper. For more complete information, the reader can refer to [30], [54] and [55]. The complexity of the mechanisms that contribute to the cloud charge structure and their scale diversity in terms of space, time and magnitude, makes their numerical representation difficult. A lot of effort has been made over the last decades, especially with laboratory experiments, in order to evaluate and understand the different factors that influence the sign and magnitude of the charge transfer. Another effort has been spent in the development of new lightning detection systems. In this sense, measurements from LMA have considerably advanced our knowledge of the electrical structure of storms and the cloud environment where lightning occurs and propagates. The LMA allows research with multiple applications to be developed, to understand the physics of lightning and storm electrification and for operational meteorology.

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Acronyms

CAPE (Convective Available Potential Energy)
EL (Equilibrium Level)
LFC (Level of Free Convection)
LEWPs (Line Echo Wave Patterns)
MCSs (Mesoscale Convective Systems)
UMIST (University of Manchester Institute of Science and Technology)
CCN (Cloud Condensation Nuclei)
VHF (Very High Frequency)
STEPS (Severe Thunderstorm Electrification and Precipitation Study)
LMA (Lightning Mapping Array)
STERAO (Stratospheric-Tropospheric Experiment Radiation, Aerosols and Ozone)

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