2015 5-th International TEPA Symposium
Thunderstorms and Elementary Particle Acceleration
October 5-9 | Nor Amberd | Aragatsotn Province | Armenia

Research of the thundercloud electrification by facilities of Aragats Space Environmental Center

A. Chilingarian, T. Karapetyan, D. Pokhsraryan

A.Alikhanyan National Lab (Yerevan Physics Institute), 2, Alikhanyan Brothers, Yerevan 0036, Armenia

Abstract. The problem of thundercloud electrification is one of the most difficult ones in the atmospheric physics. Structure of electric fields in the cloud escape from the detailed *in situ* measurements; few balloon flights recognize rather complicated structure much more sophisticated than a simple dipole or triple. To get insight into the problem of charge structure of thundercloud we use new key evidence – the fluxes of particles from thundercloud, the so-called Thunderstorm Ground Enhancements – TGEs. TGEs originate from electron acceleration and multiplication processes in the strong electric fields in the thundercloud and the intensity and energy spectra of electrons and gamma rays as observed at the Earth's surface are directly connected with the charge structure of the cloud.

In the presented paper we demonstrate that experimentally measured patterns of the near-surface electrostatic field during TGEs are consistent with triple structure of the cloud electrification. The maximal particle flux and energy spectra extended above 4 MeV coincide with special pattern of the disturbances of the near surface electrostatic field–the "bumps" arising from deep negative electrostatic field domain. These features we identify with development of mature Lower Positively Charge Region (LPCR), with development of which the electric field in the cloud get enough strength to unleash the Runaway Breakdown (RB) process accelerated electrons downward in the direction of earth.

1. INTRODUCTION

One of the main problems of the atmospheric electricity is the research of the spatial-temporal structure of the electric field in the thunderclouds. Accurately measuring the electric potential within thunderclouds is extremely difficult because of the large time variability and the need to make spatially separated simultaneous measurements within the highest field regions of the storm (Dwyer, 2005). Qie et al., 2005 observed a triple charge structure with a large Lower Positively Charge Region (LPCR) in thunderclouds over the Tibetan Plateau of China, and noticed that the large LPCR prevents negative CG flashes from occurring and, instead, facilitates negative IC flashes. Nag and Rakov, 2009 investigated the dependence of both of lightning types on the magnitude of the LPCR region. They also inferred that when the magnitude of LPCR region is large, inverted IC flashes are expected to occur; when the LPCR starts to decay negative CG flashes became possible. Therefore, LPCR has a great impact on the lightning initiation and type. Thus, how do the size and thickness of LPCR affect lightning discharges? And how to estimate the charge magnitude and distribution range of a LPCR?

To answer these questions, we use a new type of key evidence in the atmospheric electricity research, namely particle fluxes from the thunderclouds, the so-called, Thunderstorm Ground Enhancements (TGEs, Chilingarian et al., 2010, 2011). Origin of the fluxes of electrons, gamma rays and neutrons detected on the earth's surface are the Runaway Breakdown (RB) process (Gurevich et al., 1992) nowadays mostly referred to as Relativistic Runaway Electron Avalanches (RREA, Babich et al., 2001, Dwyer, 2003) and Modification of the energy Spectra of the electrons (MOS, Chilingarian, Mailyan and Vanyan, 2012). Chilingarian and Mkrtchyan, 2012 relate particle fluxes to the origination of the LPCR. The technique of detecting particle fluxes simultaneously with measuring near-surface electrostatic field and lightning occurrences, first developed on Aragats, allows to monitor the creation of the LPCR and its contraction. The maximal intensity of TGE pointed on the maximal electric field in the cloud and, correspondingly, on the maximal dimension and charge of the LPCR. Fading of the gamma ray flux evidences the degradation of the LPCR.

In (Chilingarian, 2014) we demonstrate that TGEs occur when relative humidity exceeds 95% at near freezing temperatures and that the rain abruptly terminates TGE. Thus, we conclude that LPCR resides on the rain droplets and the polarization of the droplets can play a role in the enhancement of the electric field strength in the cloud. Investigation of the Lightning-TGE relations based on one-second time series of particle fluxes reveals that usually the lightning terminates particle fluxes (Chilingarian et al., 2015). In the time less than one-second particle flux can diminish 2 and more times and return to the background value. Recent observations with microsecond-scale electronics (Chilingarian et al, 2016) proved that the initiation of TGE is connected with the very first stages of the lightning initiation and the space-temporal structure of the TGE can map fast processes of lightning initiation.

2. INSTRUMENTATION

The main goal of the GAMMA detector (also referred to as Aragats Multidirectional Muon Monitor – AMMM, Chilingarian et al., 2003) measuring the Extensive Air Showers (EASes, Fig. 1) is to recover the energy spectra of cosmic rays to understand their origin and particle acceleration mechanisms. About three hundred 5-cm thick 1m^2 scintillators overviewed by photomultipliers are measuring the number of electrons in the EAS and estimate the size and the "age" of shower and finally the energy and type of the primary particle. EAS detectors are triggered arrays; however, each detector separately counts all incident particles, thus measuring the one-minute time series of the changing fluxes of the secondary cosmic rays. GAMMA detectors consist of 2 parts: the surface array consists of 50 scintillators and the underground muon-detecting array consists of 200 scintillators. The muon array is located in the underground hall of the ANI experiment under 15 meters of soil and concrete and 12 cm of iron bars. Only muons with energies greater than 5 GeV can reach this underground detector. The 1-minute time series of the 90 scintillators located in the underground hall continuously monitor the 5 GeV muons flux to register violent solar events (see for instance Bostanjyan and Chilingarian, 2007) or nearby supernovae explosions.

Large area of the surface array makes it ideal for measuring additional electron flux correlated with thunderstorms (relative error of the 1-minute count rates is 0.13%, we use only 27 scintillators from the 50 located on the roof of GAMMA calorimeter, see Fig. 1).

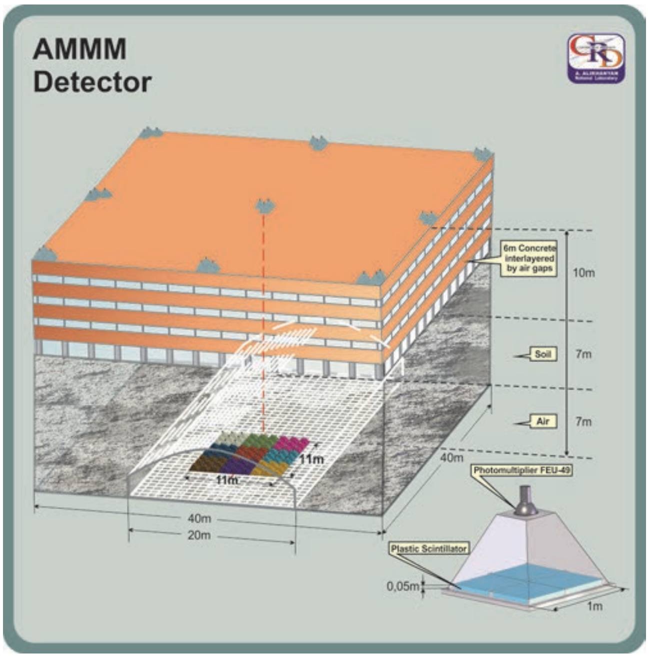

Figure 1. The GAMMA (AMMM) detector.

2.1. NETWORK OF STAND1 DETECTORS AND EFM-100 ELECTRIC FIELD MILLS

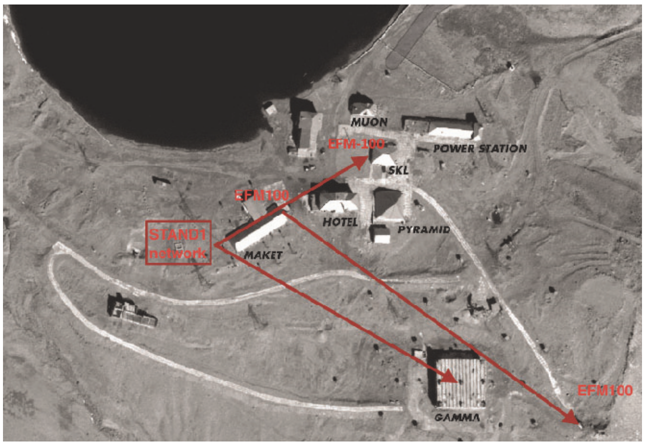

Figure 2. Network of STAND1 detectors and EFM-100 electric field sensors (electric mills); distance from MAKET to SKL ~ 100 m, from MAKET and SKL to GAMMA ~ 300 m

The STAND1 detector consists of 3 vertically stacked one-cm thick 1m^2 plastic scintillators and a stand-alone 3cm thick plastic scintillator of the same type (see top of Fig. 3). In the bottom of Fig. 3 we show 50msec time series of count rates of upper scintillators of the STAND1 detectors located near the experimental halls MAKET and SKL 100 m apart from each other. Both scintillators enhance the count rate at 14:42 – 14:46 on October 7 2015, registering strong TGE (the minute of the maximal flux has enhanced by ~100 standard deviations). The scatter plot shown in the center of the middle row of Fig. 3 demonstrates strong correlation of count rates measured by remote scintillators proving that radiation region in the cloud illuminates at least an area of ~ 5 x 10^4 m^2. The count rates after and before TGE, as expected, do not demonstrate any correlation (left and right scatter plots of the middle row of Fig. 3). Maximums of TGE at ~14:44 is registered by STAND1 scintillators approximately at the same time; thus it was not possible to estimate the structure of the emitting region in the cloud by measuring the time delay and comparing it with the wind velocity and direction. With the new, installed on the roof of GAMMA calorimeter (see Fig. 1), third STAND1 detector located at a larger distance, ~ 300 m, from other detectors it will be possible to investigate the structure of the LPCR above the detectors location site.

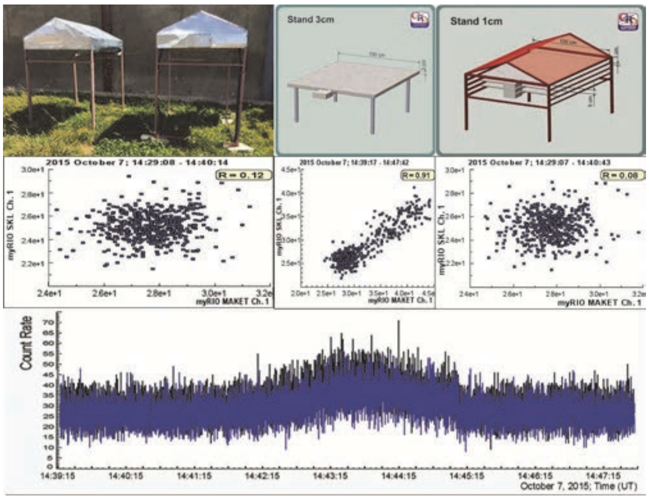

Figure 3. STNAD1 detector located nearby SKL building and its chart (top); scatter plots of count rates of the upper scintillators of 2 remote detectors (distance ~100m, middle); 50 msec time-series of the upper scintillator of the same detectors (bottom).

3. PATTERNS OF THE DISTURBANCES OF ELECTROSTATIC FIELD AND DYNAMICS OF TGEs

In Fig. 3 we depicted the algebraic sum of the electrostatic fields generated by the 3 point charges of the triple structure above according to superposition equation:

$$E_{total} = E_N + E_P + E_{LP} =$$
$$= \frac{1}{2\pi\epsilon_0}\left\{\frac{Q_N H_N}{(H_N^2 + r^2)^{1.5}} + \frac{Q_P H_P}{(H_P^2 + r^2)^{1.5}} + \frac{Q_{LP} H_{LP}}{(H_{LP}^2 + r^2)^{1.5}}\right\}$$

$$\epsilon_0 = 8.85 * 10^{-12}\frac{F}{m}$$

where Q, E and H are the charge, induced electrostatic field and height of the 3 charged regions in the thundercloud: the main negative charged layer in the middle of the cloud (N, blue); the main positive charged layer on the top of the cloud (P, red) and transient lower positive charge region (LP, green). E_{total} (black) is the superposition (algebraic sum) of all 3 electrostatic fields; ε_0 - is vacuum permittivity measured in Farads per meter units; r (distance, horizontal axis) – is the location of the sensor measuring electrostatic field strength.

We assume a plausible value of charges and heights for our simplified model (see caption of Fig. 3). We recognize that the charges in the cloud are distributed horizontally and vertically specific for each thundercloud and these values will significantly differ from the assumed. We made a variety of calculations with different sets of charges and heights. However, what is important, every time when we introduce LPCR there appeared a “bump” arising from the negative field domain. We will look for the similar structures in the experimentally measured near-surface electrostatic field time series.

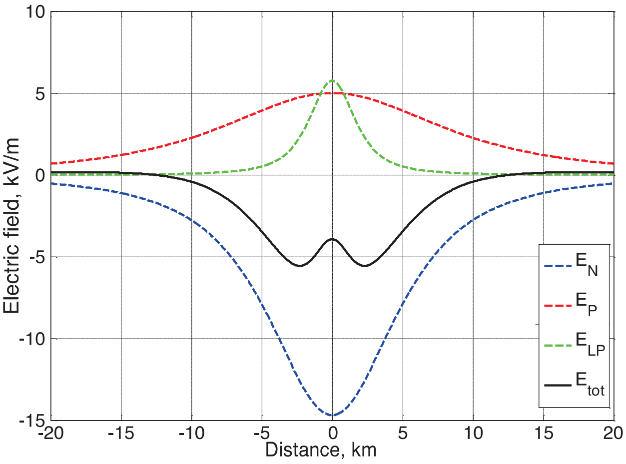

Figure 4. The electrostatic field measured on the ground due to the vertical tripole according to the “atmospheric electricity” sign convention; Q_P= 40 C;Q_N = -40C; Q_{LPCR} = 2.5C; H_P=12 km; H_N=7km; H_{LP}=2.5 km

In Fig. 5 we show a large TGE that occurred on August 28 2015. At 23:15 the near-surface electrostatic field already in negative domain (-12 kV/m) started to decrease; TGE started at the same time from the mean value of 2690 +/- 78 (2-sec time series of 60 cm thick. 1 m^2 area plastic scintillator). At 23:18 the electrostatic field dropped to -24 kV/m and the TGE reached the maximum of ~2890 (+~7%) and sustained near the maximal flux 1.5 minutes, until 23:19:30. With the TGE flux reaching its maximum, the near-surface electrostatic field started to rise, reaching -14 kV/m at 23:19:30. After 23:19:30 TGE slowly faded, recovering the “pre-TGE” value at 23:28. Electrostatic field in the same time abruptly declined, reaching -27 kV/m at 23:20; after reaching minimum, it started to rise again, touching the positive domain at 23:23 and reaching +9 kV/m after 30 seconds. Thus, at TGE maximal flux we see a well-developed bump of 12 kV/m amplitude and 2 minutes duration coinciding in time with TGE maximal flux on rising phase.

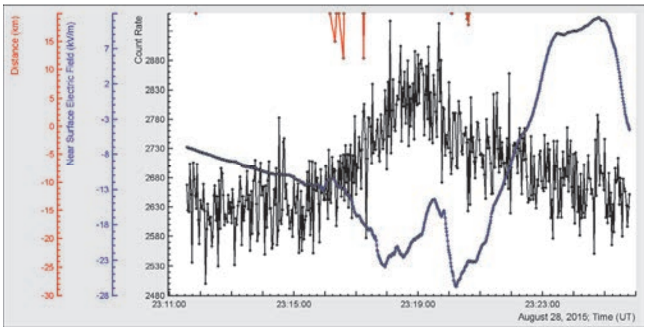

Figure 5. 2-second time series of 60 cm thick and 1 m^2 area plastic scintillator and 1-sec time series of near-surface electrostatic field with a “bump” at particle maximal flux; on the top – distance to lightning.

The emerging structures in the time series of the near-surface electrostatic field are comparable with the structures in the calculated superposition of electrostatic fields induced by 3 charges mimicking a tripole structure of the thundercloud (Fig. 4). Of course, the theoretical curve reveals the spatial distribution of the electrostatic field and the experimental ones – temporal distribution. However, the wind during TGEs is moving the cloud above particle detectors “mapping” the space distribution of the electrostatic field to the temporal one. We speculate that when the mature LPCR arrives (or emerges) above the detector location the lower dipole accelerates the electron in the direction of earth providing maximal flux of bremsstrahlung gamma rays. Electron flux reaching maximum when LPCR is above detectors and with moving of the cloud from the detector site the TGE subsequently terminates. Thus, the maximal flux of a TGE corresponds to the matureness (maximal thickness - maximal charge) of LPCR. In the time series of the electrostatic field measured at particle detector site, this episode reflected in the sizeable “bumps” rising from the deep negative domain of the near-surface electrostatic field. Note also that during the maximum of particle flux (mature LPCR) usually no lightning occurred (on the special case of TGEs terminated by lightnings see Chilingarian and al., 2016).

In the Fig. 6 we show the time series of count rate of a network of twenty-seven five cm thick 1m^2 plastic scintillators of the AMMM array (Large TGE occurred on 25 August 2015). We can notice the same bump-like structure coinciding with maximal TGE flux.

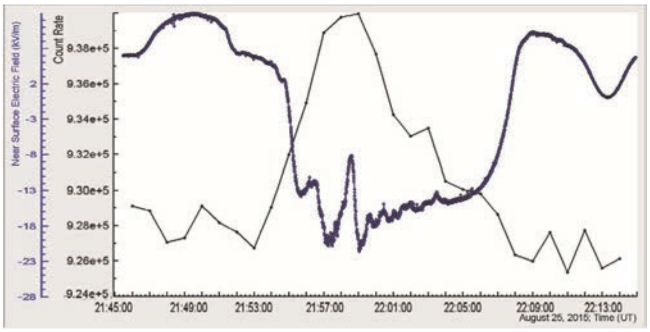

Figure 6. 1-minute time series of 5 cm thick plastic scintillator array and 1-sec time series of near-surface electrostatic field with a “bump” at particle maximal flux.

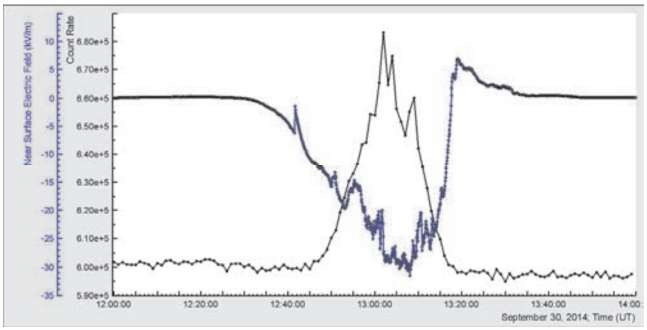

Figure 7. 1-minute time series of 5 cm thick plastic scintillator array and 1-sec time series of near-surface electrostatic field with several “bumps” corresponding to the particle flux bursts.

Another example of the disturbances of near-surface electrostatic field during a TGE we show in Fig. 7. A network of twenty-seven 5 cm thick 1m^2 scintillators measures TGE. Prolonged TGE, lasting 35 minutes demonstrate several peaks (the largest is 13% height above background equivalent to 70σ statistical significance). Carefully examining the Figure, we can outline several small “bumps” corresponding to TGE peaks.

4. CONCLUSIONS

From the observed patterns of electrostatic field disturbances during the TGE occurrences we deduce that rising “bumps” in the time series are an essential characteristic of the thunderstorm, evidencing creation of the LPCR and, as a rule - development of a large TGE. Experimentally measured patterns of the near-surface electrostatic fields during TGEs are consistent with tripole structure of the calculated electrostatic field in the cloud. The maximal particle flux coincides with the "bumps" rising from negative electrostatic field. This feature we categorize with the development of mature LPCR, which with the main negative charge layer above forms dipole, accelerated electrons downward in the direction of earth. Thus, the scenario of the TGE development (Chilingarian, 2014) finds its proof also in the measured shapes of the electrostatic field disturbances during TGEs observed on Aragats.

However, the large variability in duration, amplitude and shape of TGEs detected by ASEC facilities (see Chilingarian, Karapetyan and Melkumyan, 2013) as well as fluctuating patterns of the near-surface electrostatic field disturbances support different scenarios of the emergence of electric field strong enough to accelerate electrons downwards. Recently was discovered downward RREA occurred between the negative screening layer and the upper positive charge layer just below it (Kelly et al., 2015). Following this discovery we can consider possibility of the particle flux initiation by the electric field originated between main negatively charged region and its "charge image" of the opposite sign on the ground. Extension of the negative layer's image should be much larger than size of the LPCR due to much smaller size of the LPCR.

In 1963 Richard Feynman wrote: "The top of the thunderstorm has a positive charge, and the bottom a negative one— except for a small local region of positive charge in the bottom of the cloud, which has caused everybody a lot of worry. No one seems to know why it is there, how important it is—whether it is a secondary effect of the positive rain coming down, or whether it is an essential part of the machinery. Things would be much simpler if it weren't there". To our present knowledge LPCR is an essential condition for the TGE development and, in turn, TGE is vital for the realizing of the lightning stroke. Thus, without this "local region of positive charge" maybe no lightning will be possible and our planet will be silent and dark.

ACKNOWLEDGEMENT

Authors express their gratitude to E. Mareev for stimulating discussions and to S.Sogomonyan and G.Kanikyanc for calculating of the superposition of electrostatic field induced by thundercloud's charged layers (Fig. 3).

REFERENCES

- Babich, L.P., et al., 2001. Comparison of relativistic runaway electron avalanche rates obtained from Monte Carlo simulations and kinetic equation solution. IEEE Trans. Plasma Sci. 29 (3), 430–438.
- Bostanjyan N., Chilingarian A., 2007. On the production of highest energy solar protons at 20 January 2005, J. Adv. Space Res. 39, (1456-1459).
- Chilingarian, A. Avakyan K., Babayan, V. et. al, 203. Aragats Space-Environmental Center: Status and SEP Forecasting Possibilities. Journal of Physics G: Nucl.Part.Phys, 29, 939-952.
- Chilingarian, A., Arakelyan, K., Avakyan, K.et al., 2005. Correlated measurements of secondary cosmic ray fluxes by the Aragats space-environmental center monitors, Nucl. Instrum. Methods A 543 (2–3) 483.
- Chilingarian, A., A. Daryan, K. Arakelyan, A. Hovhannisyan, B. Mailyan, L. Melkumyan, G. Hovsepyan, S. Chilingaryan, A. Reymers, and L. Vanyan L.,2010. Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons, Phys. Rev. D, 82, 043009.
- Chilingarian, A., Hovsepyan, G., Hovhannisyan, A., 2011. Particle bursts from thunderclouds: natural particle accelerators above our heads. Phys. Rev. D: Part. Fields 83 (6), 062001.
- Chilingarian, A., Mkrtchyan, H., 2012. Role of the lower positive charge region (LPCR) in initiation of the thunderstorm ground enhancements (TGEs). Phys. Rev. D: Part. Fields 86, 072003.
- Chilingarian A., Karapetan T, Melkumyan L., 2013. Statistical analysis of the Thunderstorm Ground Enhancements (TGEs) detected on Mt. Aragats. J. Adv. Space Res., 52, 1178.
- Chilingarian A., Hovsepyan G., Khanikyanc Y., Reymers A. and Soghomonyan S. 2015. Lightning origination and thunderstorm ground enhancements terminated by the lightning flash, EPL, 110, 49001.
- Chilingarian, A., S. Chilingaryan, and A. Reymers, 2015. Atmospheric discharges and particle fluxes, J. Geophys. Res. Space Physics, 120, 5845–5853.
- Chilingarian A., Mailyan B., and Vanyan L., 2012. Recovering of the energy spectra of electrons and gamma rays coming from the thunderclouds, Atmospheric Research 114–115, 1–16.
- Feynman R., Leighton R.B., Sands M., 1963.The Feynman Lectures on Physics Vol. II Ch. 9- Electricity in the Atmosphere,edited by M.A. Gottlieb and R. Pfeiffer, California Institute of Technology.
- Gurevich, A.V., Milikh, G.M., Roussel-Dupre, R., 1992. Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. Phys. Lett. A 165 (5-6), 463–468.
- Dwyer, J.R., 2003. A fundamental limit on electric fields in air.Geophys. Res. Lett. 30 (20), 2055.
- Dwyer, J. R. 2005.The initiation of lightning by runaway air breakdown, Geophys. Res. Lett., 32, L20808.
- Kelley N.A., Smith D.M., Dwyer J.R., et al., 2015. Relativistic electron avalanches as a thunderstorm discharge competing with lightning, Nature communications, DOI: 10.1038/ncomms8845
- X. Qie, T. Zhang, C. Chen, G. Zhang, T. Zhang, and X. Kong, 2009. Electrical characteristics of thunderstorms in plateau regions of China, Atmos. Res. 91, 244.