C. R. Physique 3 (2002) 1325–1333

Physique appliquée/*Applied physics*

MÉCANISMES PHYSIQUES DU NUAGE D'ORAGE ET DE L'ÉCLAIR

THE PHYSICS OF THUNDERCLOUD AND LIGHTNING DISCHARGE

A lightning initiation mechanism: application to a thunderstorm electrification model

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Note presented by Guy Laval.

Abstract The use of numerical models has greatly increased our understanding of the electrical and microphysical process within electrified clouds. We use the University of Washington, 1.5-dimensional thunderstorm model to examine the effects of including a runaway electron based lightning initiation mechanism. We find that this mechanism can significantly alter the electrification history of modeled storms and produce vertical electric field profiles that are very similar to those of observed storms. ***To cite this article: R. Solomon et al., C. R. Physique 3 (2002) 1325–1333.***

numerical model / thunderstorm electrification / lightning initiation / runaway electrons

Un mécanisme de déclenchement de l'éclair : application à la modélisation du nuage d'orage

Résumé L'utilisation des modèles numériques à considérablement augmenté notre compréhension des processus électriques et microphysiques dans les nuages électrisés. Nous utilisons un modèle 1.5D du nuage d'orage, développé par l'Université de Washington, dans lequel on introduit un mécanisme de déclenchement de l'éclair par es électrons « runaway ». Il apparaît que ce mécanisme peut modifier de manière significative le développement de l'électrisation dans le nuage ainsi modélisé, et conduire à des profils verticaux de champ électrique calculé très similaires à ceux observés expérimentalement. ***Pour citer cet article : R. Solomon et al., C. R. Physique 3 (2002) 1325–1333.***

modèle numérique / électrification d'orage / déclenchement de foudre / électrons runaway

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S1631-0705(02)01415-9/REV

1. Introduction

Modeling of cumulus clouds, and especially thunderstorms, is challenging due to the wide range of important spatial and temporal scales. The usual approach to this task has been to explicitly model the processes of interest and to parameterize the others. Until somewhat recently, most numerical models have not been overly concerned with charge generation and lightning simulation. Meso-scale models have a complex 3-D framework utilizing a bulk microphysical scheme to allow the model to be run in a timely fashion and within the constraints placed by computers. However, since charge transfer mechanisms are sensitive functions of particle size [1], modeling the cloud electrification can be met only by explicit representation of the size dependent microphysical processes. Solomon and Baker achieve this goal by using a one-and-a-half dimensional dynamic model for dynamic simplicity and short execution time for simulations. The model utilizes the Saunders et al. [1] charge separation parameterization and includes 80 categories of water and 80 categories of ice, differentiated by mass; see Solomon and Baker [2] for more details. The geometric simplicity also allows for the inclusion of a lightning parameterization [3].

In Section 2 we discuss the numerical modeling of thunderstorms, briefly reviewing some of the current thunderstorm models that include a lightning parameterization. Section 3 discusses a theory in which in-cloud, electric fields can accelerate high energy electrons producing a region capable of initiating lightning. This mechanism is incorporated into the University of Washington thunderstorm model and results from this are presented in Section 4.

2. Numerical modeling of thunderclouds

Until somewhat recently, most modeling studies of thunderstorms focused on the early stages of electrification, those stages before the first lightning event. The ability to model the later stages of thunderstorm development has been hampered by a lack of a reasonable representation of the lightning channel and its modification to the charge within the cloud. Baker et al. [4] prescribed the endpoints of lightning channels (for both intra-cloud and cloud-to-ground) as well as the amount of charge transferred per flash. Ziegler and MacGorman [5] assume that lightning removes charge in regions of the cloud where the charge density exceeds some threshold. Neither of these models fully utilizes the information provided by ground-based, in situ and remote sensing observations to improve out understanding of lightning producing clouds.

The few lightning parameterizations in use that do attempt to account for lightning development are largely based on the ideas of Kasemir [6], Mazur and Ruhnke [7] and Helsdon et al. [8]. In these conceptual models, the lightning channel is thought of a conductor placed within an ambient electric field. If the lightning channel does not touch ground there is no net charge on the channel and the channel carries a spatially nonuniform charge density. At the end of the channels existence, the charge induced on the channel travels some distance into the cloud, modifying the in-cloud charge distribution.

Using a 2-dimensional numerical cloud model, Helsdon et al. [8], represent the lightning channel as a prolate ellipsoidal conductor placed with its long axis along the in-cloud electric field and initiated where the electric field exceeds some threshold, E_{thresh}. The endpoints of the channel are determined by the requirement that ambient electric field fell below $150\ \mathrm{kV \cdot m^{-1}}$, a value suggested by laboratory experiments [9]. As Helsdon et al. point out, this does not take into account the field of the induced charges themselves and does not allow for cloud-to-ground lightning.

Solomon and Baker [2] follow a similar approach; however, they do take the electric field induced at the tip of the channel into account. This allows the channel to propagate much further as the field at the tip may exceed the $150\ \mathrm{kV \cdot m^{-1}}$ threshold suggested by Griffiths and Phelps in regions where the ambient electric field is much less and allows for the development of cloud-to-ground lightning channels. As before, if the channel does not touch ground, the net charge on the channel is zero. If the channel does touch ground, enough charge is added to the channel to bring it to zero potential with respect to the potential of the lightning channel itself. These parameterizations are essentially 1-dimensional and do not allow for branched channels which will more than likely prove to be very significant in accurately determining the amount and location of charge actually transferred by lightning.

It is important to note that none of the lightning parameterizations currently in use attempt to include a physically based lightning initiation process. Rather, when the in-cloud electric field reaches some value near the maximum observed electric field within clouds, the lightning event is assumed to start with a small, well developed lightning channel and allowed to propagate. The transition between an electrified cloud and a cloud capable of producing lightning is not well understood. This is due in large part to a lack of knowledge about the processes in which weak, in-cloud electric fields can be enhanced to produce a local increase in the electric field resulting in propagating streamers and which ultimately lead to the formation of a fully ionized lightning channel.

Fig. 1 shows a typical model predicted time evolution of the positive and negative charge centers in the inner region of a modeled cloud as well as the lightning flash rate taken from Solomon and Baker [2].

In this case, the model was initiated with a sounding taken from the CAPE field experiment in Florida on 29 July 1991. During early thunderstorm development, period I in Fig. 1, the conditions for charge generation have not been established within the cloud. Approximately 400 sec into the model run, period II, charging begins. This period lasts until the magnitude of the electric field between the charge centers is sufficient to initiate lightning ($E_{\text{init}} = 250\ \text{kV}\cdot\text{m}^{-1}$ at all altitudes). Period III is characterized by continued charge generation and separation and the initiation of intra-cloud lightning channels between 6 km and 7 km. Intra-cloud lightning channels generally reduce the electric field by 10–15% while maintaining cloud neutrality. The charge structure at the beginning of period II is typically a very simple electrical dipole. Sometimes a small region of positive charge exists below the main region of negative charge and a small amount of negative charge accumulates at cloud top from the screening layer currents. The thunderstorm reaches its maximum cloud top height, peak reflectivity and the largest reservoirs of charge (in excess of 150 C as shown in this example) during this time. With time and the onset of intra-cloud lightning, the vertical charge profile quickly becomes much more structured. Intra-cloud lightning channels deposit

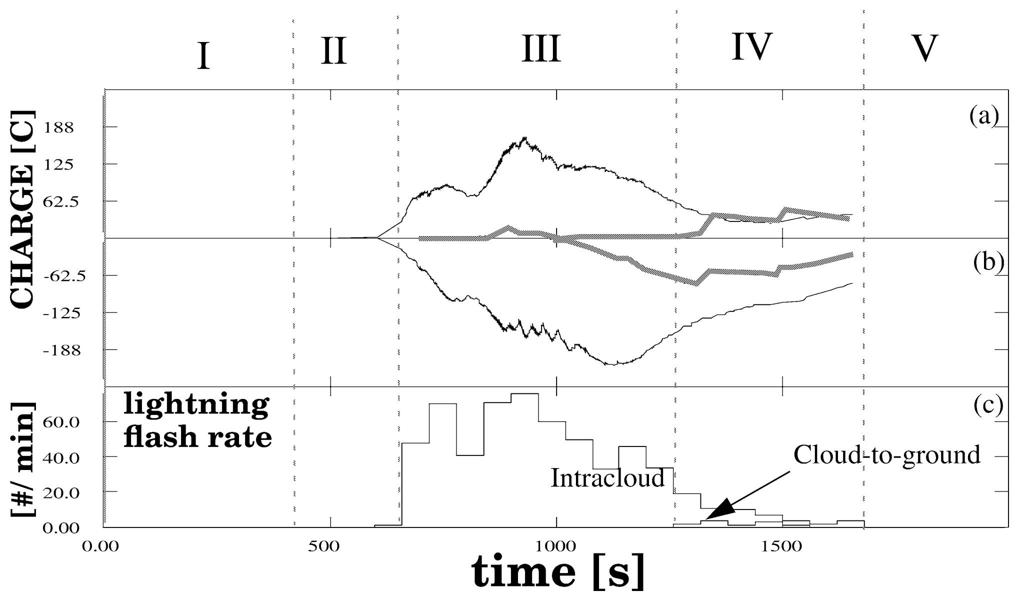

Figure 1. Time evolution of charges in the inner region of a typical model generated thunderstorm (the 29 July 1991 CaPE storm is shown here). (a) Positive charge above (black line) and below (grey line) 6 km; (b) the negative charge above (solid) and below (grey line) 5 km; and (c) number of lightning flashes per minute (intra-cloud and cloud-to-ground). Copyright 1998 and reproduced by permission of American Geophysical Union (from [2]).

positive charge in and around the lower negative charge region and negative charge in the upper regions of the cloud. Cloud-to-ground lightning channels, marking the beginning of period IV, are initiated when sufficient positive charge has been deposited below the lower negative charge region to raise the magnitude of the electric field to greater than the initiation value below the lower negative charge region. The main supplier of positive charge to this lower region is charge deposited from long intra-cloud channels. In addition, cloud-to-ground channels are also initiated as the main region of negative charge begins to descend as the updraft begins to subside, allowing the image charge to be more influential on the electric field between the cloud and ground. Both intra-cloud and cloud-to-ground lightning flashes continue until the charging rate no longer maintains a sufficient amount of charge to maintain high electric fields for initiating lightning, period V. This can be due to subsiding updrafts which prevent graupel from being processed in the charging zone and the removal of liquid water from the charging zone by glaciation [2].

Due to its flexible nature, the University of Washington thunderstorm model has been successfully used to study thunderstorms in a variety of environments [2] and can easily be modified to study possible lightning initiation schemes.

3. Lightning initiation via runaway breakdown

Little is known about lightning initiation which appears to occur when the magnitude of the electric field is $\frac{1}{10}E_{\mathrm{breakdown}}$, where $E_{\mathrm{breakdown}}$ is the electric field needed for electrical breakdown of dry air, $E_{\mathrm{breakdown}} = 2600\ \mathrm{kV\cdot m^{-1}}$ at sea level. After a period of "preliminary breakdown" within the cloud, lasting tens of milliseconds, a branched discharge propagates bi-directionally away from the initiation. Sharp increases in X-ray fluxes have been detected above thunderstorms [10,11], adjacent to thunderstorms [12] and at the ground [13] just preceding and during large electric field changes. This indicates that energetic electrons (i.e., those with energies 1 MeV or greater) are accelerated in the electric fields.

According to the runaway breakdown hypothesis, these energetic electrons are descendants of high energy electrons produced aloft by in situ radioactivity and (in far greater numbers) by galactic cosmic rays. An electron of around 1 MeV can accelerate despite the continued collisions and collisional energy losses if the electric field exceeds some threshold. This threshold field $E_{\mathrm{be}}(p)$ is called the breakeven field and the accelerating electrons are termed runaways. $E_{\mathrm{be}}(p)[\mathrm{kV\cdot m^{-1}}] \approx \pm 200p$ where p is in atmospheres. Thus this breakeven field is approximately an order of magnitude less than the dielectric breakdown field. The near equality of this breakeven field with the maximum field in thunderstorms [14] supports the runaway breakdown mechanism.

Gurevich et al. [15] have suggested that high energy electrons are produced aloft by very high energy cosmic ray particles. Little is known about the distribution of this source, but estimates indicate it is sufficient to account for the thunderstorm climatology observed. (Since we confine our attention to very high energy cosmic ray particles, they are not deflected by the Earth's magnetic field and thus their flux is not highly latitude dependent.) Radionuclide decay aloft may be another source of the initial electrons, particularly in regions where convective activity is enhancing the flux of ground based nuclides to the upper troposphere. The measured X-ray bursts tend to last a few milliseconds, which is long compared with expected cosmic ray events, lending support to the latter idea. If these electrons find themselves in a region (associated with a thunderstorm) in which the electric field strength is greater than the local breakeven field over sufficient distance, their interactions with air molecules can produce copious numbers of daughter electrons, some of which also can become runaways. If sufficient numbers of these are formed, the ensuing charge density can be high enough locally that the conductivity can rise dramatically, and with it the local electric fields, which can thus reach $E_{\mathrm{breakdown}}$. This mechanism, then, is one way to produce small scale enhancement of rather weak electric fields and thus give rise to lightning. Fig. 2 [16] shows a schematic of this process; see Solomon et al. [16] for more details.

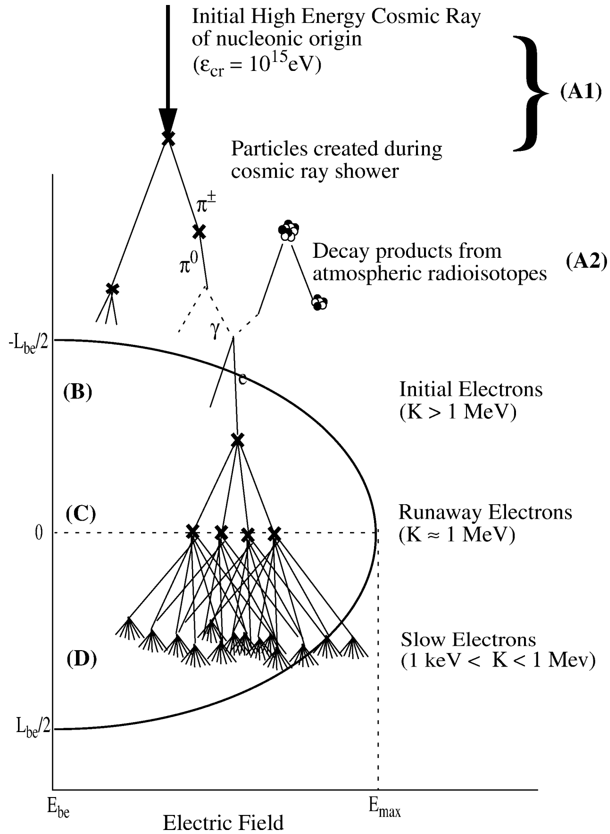

Figure 2. Sketch of electron multiplication processes in the region of a thunderstorm in which $E(z) \geqslant E_{\mathrm{be}}$ in the runaway breakdown model. This region is assumed to be of depth L_{be} centered around z_{max}, the altitude above the surface at which the field reaches its maximum value, E_{max}. The point A1 shows the precursor processes in the case that the high energy electrons are produced from cosmic ray particles and point A2 the case that precursor processes arise from in situ radioactivity. See text. Copyright 2001 and reproduced by permission of Royal Meteorological Society (from [16]).

Solomon et al. [16] have shown that in order for breakdown fields to be produced by the runaway breakdown mechanism the breakeven field must be surpassed for distances on the order of a kilometer under realistic atmospheric conditions.

Balloon soundings do not show these large transient field excursions. There are two possible reasons for this: (i) relaxation via flow of background electrons in the fields; and (ii), the long time constants characteristic of current balloon instrumentation. There is a natural ‘choke’, or relaxation process that acts to diminish the electric fields created by the external source of high energy electrons. This relaxation occurs as background runaway electrons are accelerated in the high fields, produce daughter runaways and modify the in-cloud electrical conductivity, thus decreasing the field due to the shower. However, this process is relatively slow; the relaxation time for a range of relevant conditions is on the order of 0.1–10 s.

4. Results

For our series of sensitivity tests, we have modified the University of Washington thunderstorm model to include the lightning initiation mechanism and in-cloud charge modification scheme detailed previously (Section 3) [15–17]. If $E > E_{\mathrm{be}}$ over a sufficient distance a lightning channel is inititiated at the base of the runaway-electron shower and allowed to propigate bi-directionaly. (See Solomon and Baker [2,3] for details on the lightning parameterization.) However, if this criterion is not met, high energy electrons reduce the field in regions where $E > E_{\mathrm{be}}$. No action is taken if E does not exceed E_{be}.

We model a convective event observed during the Mesoscale Alpine Project (MAP) on 4 October 1999. Figs. 3 and 4 show radar observations from the ERSA-CSA Fossalon Di Grado radar and cloud-to-ground

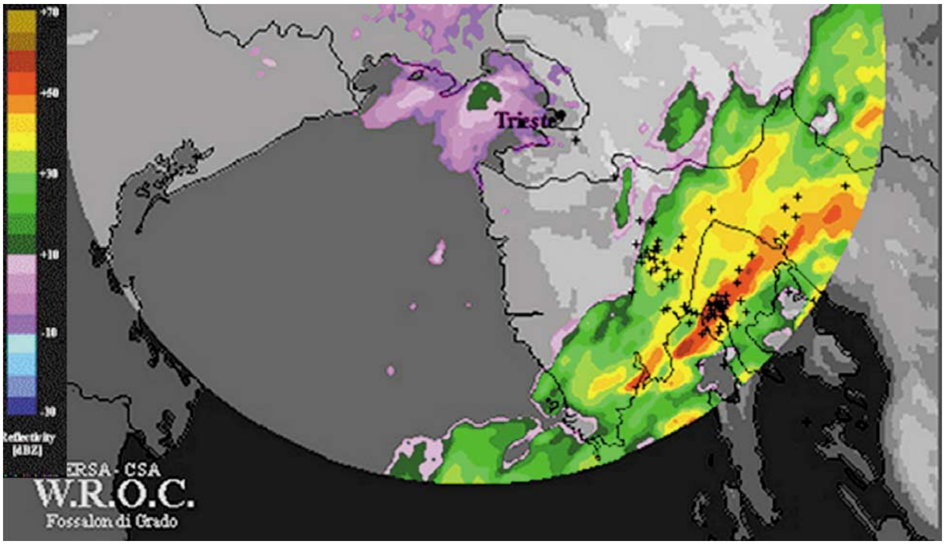

Figure 3. Vertical maximum intensity of radar reflectivity and location of cloud-to-ground lightning, small + marks, ±10 minutes of the radar scan, 4 October 1999, 5:10 UTC. The reflectivity scale ranges from +70 dBZ (top) to −30 dBZ (bottom) in 20 dBZ increments. This section of the radar roughly covers the northern, costal region of the Adriatic Sea.

lightning measurements from the Centro Elettrotecnico Sperimentale Italiano (CESI) lightning detection network.

Fig. 3 shows vertical maximum intensity of radar reflectivity and location of cloud-to-ground lightning within ±10 minutes of the radar scan, (5:10 UTC), shown by tiny pluses. Although difficult to discern, Trieste is labeled near the upper center section of the plot. The most convective regions, almost directly southwest of Trieste, have a maximum reflectivity that exceeds 50 dBZ.

Fig. 4 shows the cloud-to-ground lightning flashrate on the same day between 4:00 and 6:00 UTC. The outlined region represents the edge of the Adriatic Sea (scale of the entire picture is similar to that in Fig. 3) while each of the boxes within the gridded area represents an area within the region that is $0.25^\circ \times 0.25^\circ$. Within each boxed area the the lightning flash rate in given for a two hour period. The vertical axis of each small boxed area within grid is 0–16 flashes/minutes while the horizontal scale is time with 5:00 UTC centered on the x-axis of each small boxed area. The flash rate in the most convective regions, southwest of Trieste and where the radar reflectivity is the greatest, tends to exceed ≈8–10 flashes/minute peaking around the time of the measured reflectivity in Fig. 3.

Fig. 5 presents the cloud-to-ground and intra-cloud lightning flash rates from modeled storms initialized with a sounding from the the MAP IOP-5 Friulli, Italy area. In one case the the lightning initiation electric field equals the breakeven electric field, $E_{\text{init}} = E_{\text{be}}$, *and* includes the cosmic ray/background electron processes of Solomon et al. [16] (upper panel, referred to hereafter as ECRS) while in the other the lightning initiation electric field equals the breakeven field only, $E_{\text{init}} = E_{\text{be}}$ (lower panel, referred to hereafter as EBE).

The lightning flash rates and number are significantly lower in the ECRS simulation than the EBE case. The uniform background electrons effectively prevent the in-cloud electric field from exceeding E_{init} over vertical scales large enough to initiate lightning. However, with a large charging rate for an extended period of time, there are periods when the electric field can exceed the breakeven field over a large enough distance to initiate lightning. Both simulations give comparable values for the cloud-to-ground lightning flash rate

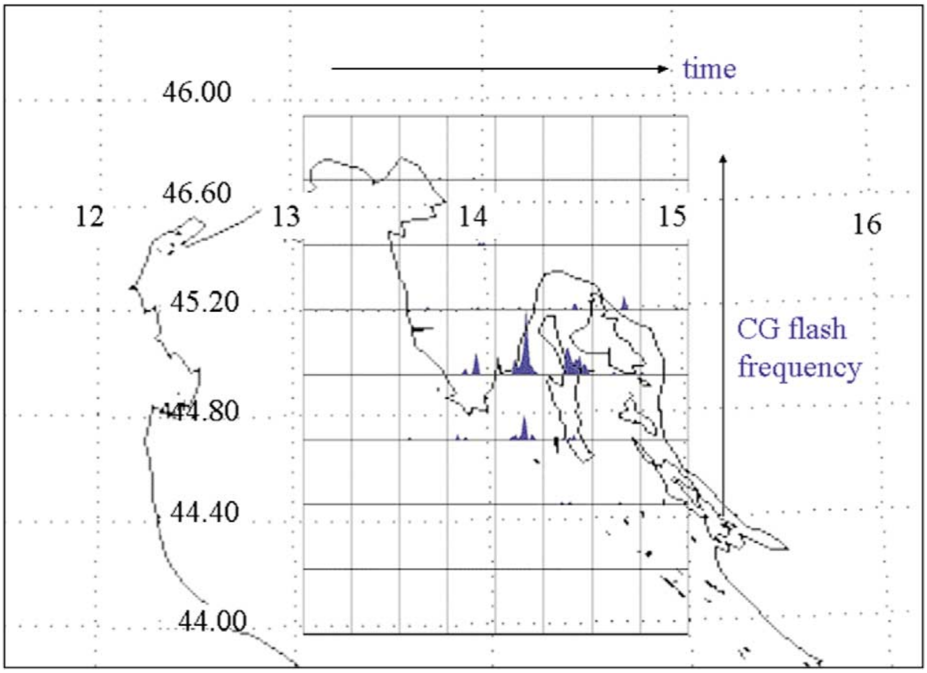

Figure 4. Cloud-to-ground lightning flash rate from CESI lightning data on 4 October 1999. The outlined region represents the edge of the Adriatic Sea (scale of the entire picture is similar to that in Fig. 3) while each of the boxes within the gridded area represents an area within the region that is $0.25^\circ \times 0.25^\circ$. Within each boxed area the the lightning flash rate is given for a two hour period. The vertical axis of each small boxed area within grid is 0–16 flashes/minutes while the horizontal scale is time with 5:00 UTC centered on the x-axis of each small boxed area. Latitude and longitude are given by the values along the left and top sides.

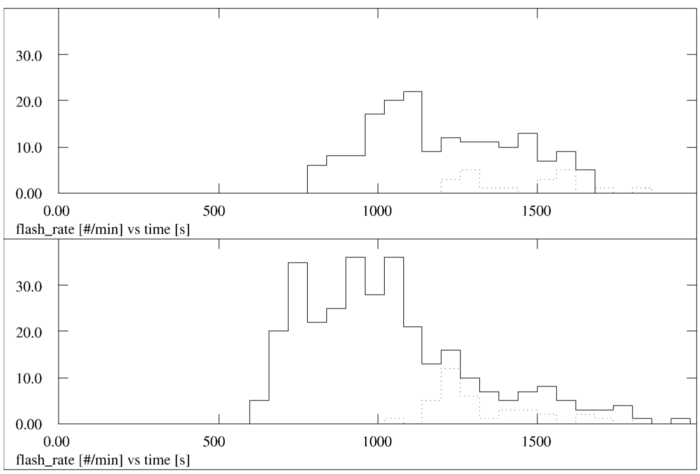

Figure 5. Modeled total lightning flash rate ($\#\,\mathrm{min}^{-1}$) versus time (sec) of a storm occurring in Friulli, Italy on 04/10/1999. Solid curves are intra-cloud flashes and the dotted line cloud-to-ground. The lower panel is the flash rate when $E_{\mathrm{init}} = E_{\mathrm{be}}$ at all altitudes. The upper panel is when $E_{\mathrm{init}} = E_{\mathrm{be}}$ and utilizes the lightning initiation and charge modification processes of Solomon et al. [16].

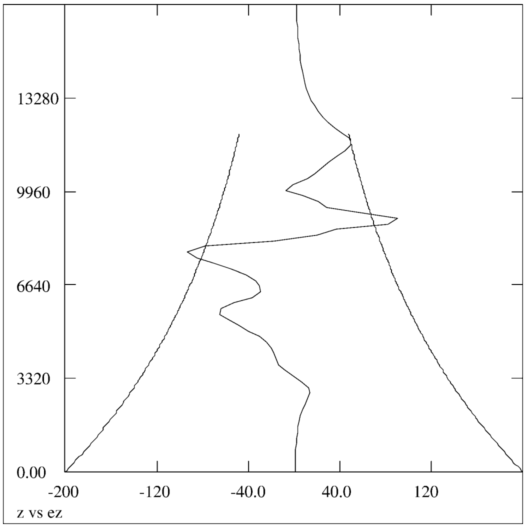

Figure 6. Modeled vertical electric field ($\mathrm{kV \cdot m^{-1}}$) as a function of altitude (m) from the ECRS case. The symmetric curves give the value of E_{be} as a function of altitude.

when compared to observations as seen in Fig. 4. The maximum modeled reflected reached 52 dBZ which also corresponds well with the maximum observed values from Fig. 3, ≈55 dBZ.

Fig. 6 shows the modeled vertical electric field at 700 seconds into the ECRS model run. Even though the electric field exceeds E_{be} at several locations, lightning is not initiated as the distance over which $E > E_{\mathrm{be}}$ is not sufficient to create an electron avalanche capable of starting a lightning channel. Lightning had commenced in the EBE case but not in the ECRS case. However, with continued charge seperation the electric field begins to exceed E_{be} over a substantial distance and lightning is initiated in the ECRS model run.

Both cases also give similar lightning flash rate patterns throughout the life of the storm. Overall, both cases exhibit similar electrical development with the largest difference being caused by the relaxation of the electric field in the ECRS case by high energy electrons when the distance overwhich $E > E_{\mathrm{be}}$ is insufficient to initiate lightning.

One interesting point that should be noted about the ECRS case, the location of lightning initiation is not necessarily at the location where the electric field is the largest, rather it near at the base of the electron avalanche. Since the distance that must be traversed by the electrons can be on the order of 1–2 or more kilometers, this may place the lightning initiation point that same distance from the peak electric field and/or where the electric field initially exceeded E_{be}.

5. Concluding remarks

The basic limitations of the thunderstorm model's lightning parameterization lie in its neglect of all but electrostatic effects in determining lightning initiation and charge redistribution due to lightning. The fact that the parameterization seems to give reasonable trends and reasonable magnitudes of charge transfer per flash appears to vindicate its use in numerical studies of electrified clouds. However, there are further limitations which could be overcome by relatively minor changes. A one-dimensional cloud and lightning model cannot capture the effects of horizontal development of charge centers, which may be of particular importance in the development of cloud-to-ground channels. While the thunderstorm model could accommodate non-vertically propagating channels, the lightning parameterization could not in its present, analytic form, be used for complicated trajectories. Extension of the shape of the conductor is in principle possible but would entail numerical computation of the charges induced on it.

Further comparisons with observations are required to determine if the CRS lightning initiation scheme produces realistic results. In particular, simultaneous in-cloud electric field measurements and lightning mapping would be useful in comparing modeled initiation points with those observed by mapping techniques.

Even with these limitations, the numerical model is a very useful instrument for conducting a large number of simulations and sensitivity studies. Its 'simplicity' also allows for the inclusion of a lightning initiation mechanism and to study its ramifications on thunderstorm development.

The importance of utilizing an explicit microphysical parameterization is becoming more and more apparent for microwave retrieval methods. Databases are populated with modeled microphysical profiles and used to determine cloud properties from observed microwave radiances. To this end, the microphysical framework of the University of Washington thunderstorm model and aspects of the lightning parameterization will be included in the University of Wisconsin 3-dimensional meso-scale model (NMS) in the future. The model can then be used to create a high resolution database of cloud microphysical water and ice spectra.

Acknowledgements. We would like to thank Renzo Bechini for providing Fig. 3.

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