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Role of Intracloud Lightning in Tornadogenesis

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13. ABSTRACT (Maximum 200 words) The role of cloud electrification within supercells and, in particular, the role of lightning in tornadogenesis is re-examined. Rather than cloud-to-ground lightning, it is intracloud lightning that is the culprit for enhancing updraft wind velocities to tornadic levels. The lightning produces within the intracloud chamber both: (1) newly generated hydrogen ions, of negligible cross-section, that stream downwards to recombine with the main resident lower cloud hydroxyl ion concentration, thereby liberating significant ionic recombination and condensation energy to produce significant temperature rise; and, (2) counterpart hydroxyl ions that sweep upward to push all in their way so as to reach the topmost cloud structure for recombination with the resident hydrogen ion concentration. To effect the significant updraft enhancement required for tornado initiation, repeated lightning strikes are required within an individual vortex “core”; and, this restriction relates to the relatively rare occurrence of tornadoes as generally minor dissipative sources of supercell energies.			
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PREFACE

This report was prepared by the Energetic Materials Branch of the Ordnance Division, Air Force Research Laboratory, Munitions Directorate (AFRL/MNME), Eglin Air Force Base, Florida 32542-5910, and covers the work period - May 2004 - December 2004.

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SECTION I

INTRODUCTION

Historical consideration of a role for lightning in tornadogenesis was focused on cloud-to-ground lightning strikes. On such basis, Vonnegut and Moore (1957) and Vonnegut (1960) provided a modern interpretation for the historically-developed notion that "tornadoes are a manifestation of thunderstorm electricity"; see Moore and Vonnegut (1977). Vonnegut had concluded that the below-cloud energy density required for achieving wind velocities of 200-250 m/s, say, over a circular area of 100 m diameter, was not achievable without a role to be played by lightning and, in particular, concluded even so that repeated strikes "through the same path for a sufficient length of time" were required to sustain tornadic action. The below-cloud lightning strikes were argued to provide two additional energy sources for wind enhancement: direct heating, as historically suggested, and through the cloud-to-ground electric field influence on accelerating charged water droplets.

Rathbun (1960) independently added to the thesis of lightning importance by arguing that tornadoes were electromagnetically fostered, first, through generation of hydrogen ions by water decomposition in cloud-to-ground lightning strikes and, then, the hydrogen ions being accelerated upwards in spiral motion to the negatively-charged lower cloud level under influence of the earth's magnetic field. Through sample calculations for birth of a mini-tornado, a charge density of 10^{10} positive ions/cm^3, taken to be generated within a potential gradient of 2 kV/cm, was reasoned to produce through neutral air collisions, a wind velocity increment of ~52 m/s (~116 mph) within a tubular vortex having a radius of 1.75 m and a wall thickness of 10 cm.

Wilkins (1964) provided an excellent critique of the Vonnegut and Rathbun model analyses for association of electrification influences during the life cycle of a tornado. He concluded, from model description of cloud-to-ground discharging through a vortex, the electrodynamic acceleration of ions was relatively unimportant and, from laboratory model experiments, the indication was that, even with important temperature rise being added, "a more or less continuous electrical discharge in the center of a vigorous aerodynamic vortex will inhibit rather than augment vortex circulation". It is important that such analysis and experiments were devoted to the issue of ground level observations having been interpreted to indicate that tornadoes were being sustained by internal lightning discharges. In the present work (Glenn and Armstrong, 2004), the topic is re-examined for two reasons: modern observations indicate that the important events for tornadogenesis occur, not on cloud-to-ground levels but, within the intracloud storm structure where electrification issues are more relevant; and, evaluation of the electrical forces, not on charged water droplets but, on individually-charged hydrogen and hydroxyl ions are greater by orders of magnitude.

SECTION II

THE INTERNAL SUPERCELL BUILD-UP TO PARTIAL LIGHTNING DISSIPATION

Amid numerous complex features of supercell development presaging partial lightning dissipation is the observed build-up of positive upper level charge concentration and negative lower level charge concentration. The initial charge generation, that is responsible for establishment of the global electric field, takes place by ice particle collisions. The particles become attached to larger hydrogen/hydroxyl/nitrous ion-associated water/ice molecule clusters or particles in a strongly convective atmosphere (Dye et al., 1986).

In such charge generation process, a fundamental role is assigned to existence of a strong intracloud updraft, whose supercell-forming charge-generation process overrides, at first, a reverse flow of negative charge to the lower cloud level. The vertical charge separation is thought to develop in more complicated churning of the "vaporous soup" than simply being the result of gravitationally-determined lower hydroxyl ion attachments to heavier particles as compared to hydrogen ion attachments to higher lighter particles. Strong frictional forces are proposed to be associated with the ice or hail particle collisions. Such build-up of vertically-separated charge densities proceeds until dielectric breakdown of the cloud resistance occurs and lightning strikes are produced. Intracloud lightning strikes are of special interest for tornadogenesis because modern researches show essentially no correlation of tornadoes with cloud-to-ground strikes (Buechler et al., 2000).

$$(m\,H_2O)_S + (n\,H_2O)_S \xrightarrow{K.E.} ([m-p]\,H_2O)_S + ([n-q]\,H_2O)_S$$

$$+ (p+q)H^+{}_V \uparrow \; + (p+q)(OH)^-_V \downarrow \qquad (1)$$

Equation (1) depicts schematically an ice particle collision/ionization/supercell formation sequence on an analogous van't Hoff reaction isotherm basis for describing chemical reactions and phase transformations. The equation describes in the simplest terms the consequence of ice particles collisions of m- and n-sized molecules splitting-off (p + q) free hydrogen and hydroxyl ion concentrations that, with, or without, subsequent particle attachments, are convectively separated to produce the global electric field of the supercell. The up-and-down arrows indicate, respectively, that upper hydrogen ion (attached particle) concentrations and lower hydroxyl ion (attached particle) concentrations build-up progressively until the electric field of the supercell becomes strong enough for dielectric breakdown.

SECTION III

A NEW CONCENTRATION OF LIGHTNING-INJECTED CHARGE CARRIERS

$$m`(H_2O)_V \overset{E_{disch.}}{\Longrightarrow} m`H^+_V \downarrow + m`(OH)^-_V \uparrow \qquad (2)$$

Equation (2) applies for the action of lightning that, at a certain cylindrical radius centered on a sensibly vertical discharge, has the major influence of converting resident water or ice molecules within the intracloud chamber into a new concentration of ionized charge carriers. The energy released in the lightning strike is very small compared to the energy stored in the supercell. Thus, in equation (2), after supercell build-up to lightning discharge, its action produces a new concentration of hydrogen and hydroxyl ions that are subjected to the remaining pervasive influence of the residual electric field of the supercell. The oppositely-charged, lightning-initiated, ions are respectively driven, along a cylindrical surface centered on the vertical lightning strike, to their opposite poles so as to annihilate the charges constituting the global electric field of the supercell. Such dual cylindrical hydrogen and hydroxyl ion fluxes are the counterpart action to Rathbun's same description for hydrogen ion action in a cloud-to-ground lightning strike. Of course, an amount of on-site recombination of the ions will diminish the intensities of the otherwise separated fluxes. If sufficient local charging occurs, an embryonic vortex is initiated that, with further spatially-localized charging by repetition of the same mechanism, is proposed to build-up to a tornado-spawning updraft.

SECTION IV

THE MECHANISMS OF UPDRAFT ENHANCEMENT

$$\downarrow m`H^{+}_{v} + (p + q)(OH)^{-}_{v} \Longrightarrow m`(H_2O)_{v}$$

$$+ (p + q - m`)(OH)^{-}_{v} ; \qquad (3a)$$

$$m`(H_2O)_{v} \Longrightarrow m`(H_2O)_{L} \qquad (3b)$$

$$\uparrow m`(OH)^{-}_{v} + (p + q)H^{+}_{v} \xRightarrow{\Delta P \uparrow} m`(H_2O)_{v}$$

$$+ (p + q - m`) H^{+}_{v} \qquad (4)$$

Equations (3a,b) and (4) provide a schematic description of the mechanisms for updraft enhancements accomplished by the lightning-spawned and oppositely-driven H+ and OH- ions. First, consider that the lightning-generated hydrogen ions are driven to the lower cloud level. As indicated in equation (3a), the m' concentration of hydrogen ions combine with their counterpart number in the lower residing (p + q) hydroxyl ion concentration that, presumably, is mostly attached to larger charged particles constituting that pole of the global supercell electric field. The ion recombination energy is approximately twenty times larger than the condensation energy of water vapor, thus supplying significant additional temperature rise to the thermal updraft, that otherwise was found lacking both by Vonnegut (1960) and Wilkins (1964) only on the water condensation basis described in equation (3b). The lightning generated m' concentration of hydrogen ions have small cross-sections so a relatively insignificant influence occurs for their downward directed collisional or momentum exchange with air mass. On the other hand, the more massive and relatively, very substantially-sized, corresponding m' concentration of hydroxyl ions, that are driven upwards by the same electric field, as in equation (4), are proposed to add a substantial pressure in that direction as they sweep all in their way towards recombination reaction at the upper cloud level, much more so than had been attributed by Rathbun (1960) to a collisional influence of upward directed hydrogen ions produced by cloud-to-ground lightning strikes. Thus, the respective oppositely charged ions each contribute in their own way to enhancing the updraft wind velocity.

SECTION V

ELECTRICAL FORCE EVALUATIONS

Vonnegut (1960) was concerned, in focusing on the role of lightning-induced ionizations in cloud-to-ground strikes, that the hydrogen ions driven upward should be attached to heavier water particles so as to accomplish effective momentum transfer to the air. He derived the relationship for electric force, **F**, on a charged water droplet as:

$$F = 9\ E^2\ L\ /\ 4\ \pi\ a \qquad (5)$$

where **E** is the electric field, **L** is the liquid water content, and **a** is the charged water particle radius. For **E** = 10 ESU/cm (= 3 kV/cm), **L** = 2 g/m^3, and **a** = 20 micrometers, a relatively small force of 0.07 dynes (= 0.7 µN) was found to act on a cubic centimeter of the cloud. The force was estimated to produce the equivalent updraft of a temperature rise of approximately 20 ^oC, somewhat disappointing. A smaller particle radius couldn't be considered, apparently, without violating the experimentally employed maximum limiting charge that could be acquired by a water particle.

Figure 1 shows graphical evaluation of the electric force acting on differently charged ion and water/ice particles as a function of their sizes, including the graphical description of Vonnegut's relationship. The closed circle point applies for Vonnegut's reported **F** = 7 x 10^{-7} N and **a** = 2 x 10^{-5} m chosen as a smallest water droplet size. The Vonnegut **F-a** relation is shown to be extended to larger graupel sizes, say, between 2 x 10^{-3} and 5 x 10^{-2} m, that are reportedly encountered in tornado-producing supercells and which are shown here to experience negligible electrical force. Dashed Vonnegut lines for larger or smaller values of **L** are drawn parallel to the solid line.

The direct evaluation of the electrical force on either species of a fully ionized concentration, **L**, in g/m^3 of water, is given by

$$F = E\ [N\ L/18]\ q \qquad (6)$$

where **N**, Avogadro's number (= 6.02 x 10^{23}) multiplied by **L** and divided by 18 g, is the total number of hydrogen or hydroxyl ions available per m^3; and, **q** is the electronic charge, 1.6 x 10^{-19} C. For **L** = 2 g/m^3, the filled square point at 100% ionization is obtained in Figure 1 at **F** = 3.2 x 10^3 N and with **a** = 0.96 x 10^{-10} m for the hydroxyl ion radius taken as the bond length. At 0.1% ionization of **L**, the filled square point is correspondingly shifted downward.

The same electrical force described for the hydroxyl ion concentration applies equally for the presumed matching population of hydrogen ions and would be plotted to the left in Figure 1 at the effective proton radius of 1.44 x 10^{-15} m. The downward acceleration of the hydrogen ions would be enhanced relative to the hydroxyl ion acceleration by a factor given by the ratio of the hydroxyl-to-hydrogen ion masses. Instead of plotting in Figure 1 the shifted **F-a** point for the hydrogen ions, the value of **F** is plotted as a filled triangle that applies for the 10^{10} hydrogen ions/cm^3 considered by Rathbun (1960) to have sufficient force and momentum capability to sweep air upwards from the below-cloud influence of a lightning strike and, hence, provide for the earliest stage of tornadic initiation. Thus, compared to both Rathbun and Vonnegut evaluations, Figure 1 demonstrates that orders of magnitude greater electric forces apply for intracloud lightning-generated ion populations under otherwise the same conditions previously considered for the other model considerations.

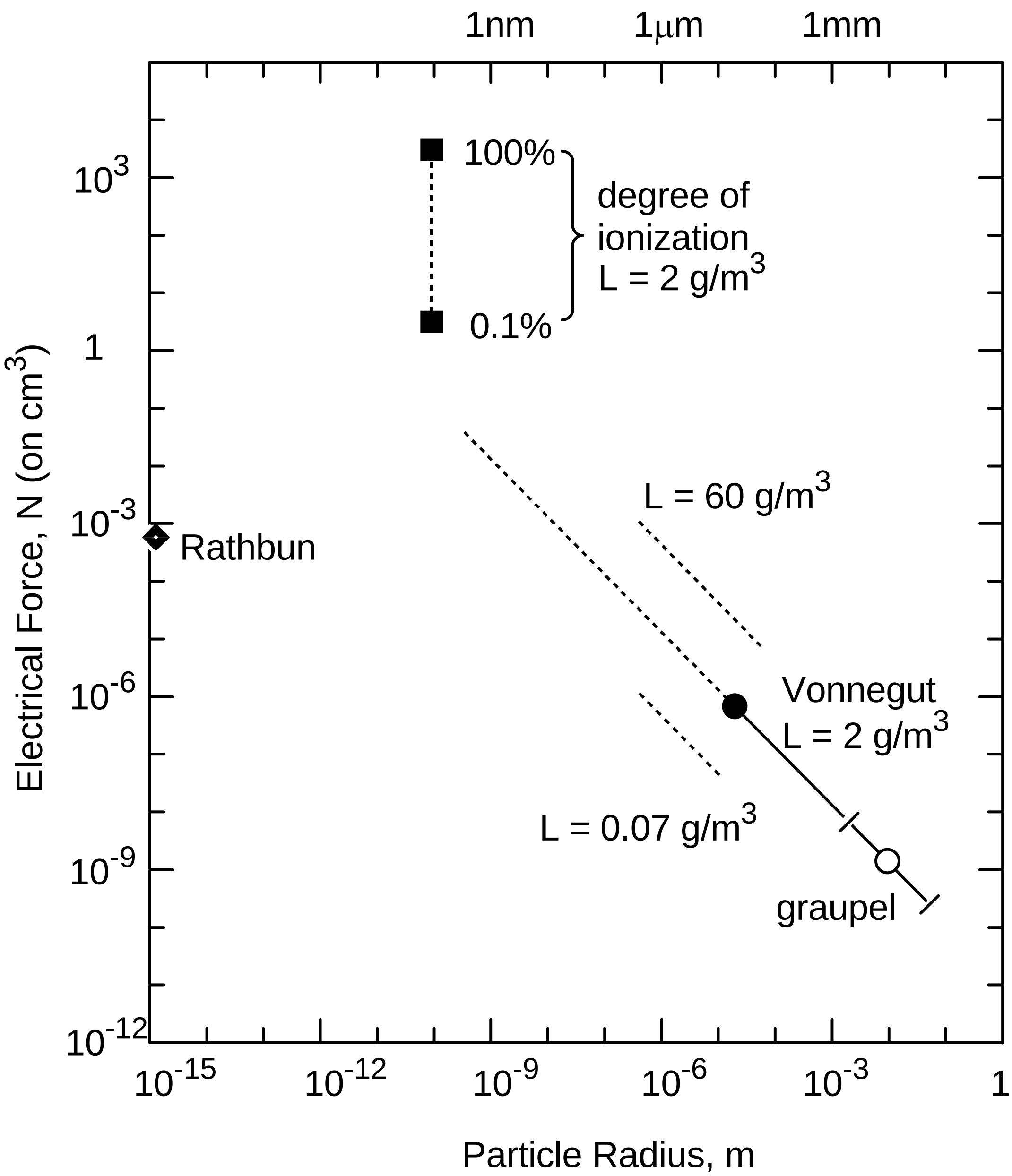

Figure 1. Electric force versus individual sizes of: H+ and OH^- ions; charged water particles; and graupel.

SECTION VI

DISCUSSION

An important consideration given emphasis by all investigators arguing for an electrification influence on tornadogenesis, whether at cloud-to-ground level (Vonnegut, 1960; Rathbun 1960) or intracloud level (Glenn and Armstrong, 2004), is that there should be repeated lightning strikes so as to provide needed build-up of the wind velocity. Vonnegut, for example, argued for 10 to 20 strikes/s to provide an estimated 10^{11} J/s of electrical energy, this being roughly “enough electrical energy to power a tornado”. In fact, Williams et al. (1999) have recently reported “jumps” in intracloud lightning flash rates of 3 to 8 strikes/s that were associated with sudden increases in wind velocities of 50 to 70 mph at ground level, and these winds were found to lag behind the flash rate jumps by 5 to 20 minutes. Such lightning precursor to the onset of a severe weather condition was interpreted, however, in terms of an enhanced updraft producing the lightning activity rather than the other way around. The present analysis, based on provision of specific mechanisms for updraft wind enhancements, gives some evidence for considering that the reverse situation applies. Whatever the current level of updraft, if a sudden increase in intracloud lightning flash rate occurs, and it is of sufficiently high level, then, very significant concentrations of hydroxyl and hydrogen ions are produced. The hydrogen ions are driven faster to recombination reaction at the lower cloud level and, thereby, produce significant upward driving thermal influence. The much larger hydroxyl ions, in turn, push upwards, producing a rising pressure influence. Both actions add to enhancement of the wind updraft beginning from the lower cloud level.

The need for repeated lightning strikes provides an additional very important spatial requirement if the lightning assistance is to build from a mini-tornado, say, of the type described by Rathbun (1960), not for the unlikely case of a charged cloud-to-ground atmosphere but for the very likely case of adding to the updraft in the intracloud environment. Such mini-vortices are easily seen physically to repel each other when having the same rotational vectors and to annihilate each other if having opposite sign rotations. Thus, the only mechanism by which truly high wind velocities might build to single tornadic condition through the enhancing influence of electrification, as considered here, is if repeated lightning strikes occur within the same spatially localized “core” of an initial vortex. But this requirement provides an opportunity of finishing this report on a positive note because such spatially localized requirement contributes an explanation for the observation that tornadoes are a relatively rare outcome even of severe weather dissipations.

SECTION VII

SUMMARY AND CONCLUSIONS

A role for intracloud electrification in tornadogenesis is described and shown to constructively relate to pioneering researches that were earlier applied to cloud-to-ground electrification concerns. The indication is that lightning-generated hydrogen and hydroxyl ions in the intracloud atmosphere are active particles adding to wind velocity build-up. Evaluation of the electrical force on these primary particles shows it to be greater by orders of magnitude than those associated with larger water particle sizes. Lightning-generated hydrogen ions are driven downwards to recombine at the lower cloud level with resident supercell hydroxyl ions, particle-captured or not, and thus add significant thermal influence for updraft wind development. The counterpart lightning-generated hydroxyl ions are driven upwards to effect significant collisional action on various air particles in the intracloud chamber, thus adding an upward pressure influence to wind velocities. In order to provide sufficient updraft build-up to tornadic level wind velocities, repeated lightning strikes are required to be spatially localized within an embryonic vortex "core". The requirement appears to be in line with recent experimental observations associating severe wind velocity build-ups and "lightning rate jumps"; otherwise, the requirement of spatial localization of the lightning is concluded to provide part of the explanation for tornadoes being relatively rare occurrences.

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