ROLE FOR LIGHTNING IN TORNADOGENESIS AND POSSIBLE MODIFICATION

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Abstract. New consideration is given to the action, under severe storm conditions, of repeated, spatially-localized, intracloud lightning flashes providing enhancement of updraft wind velocities towards initiation of a tornado. The basis for the updraft wind enhancement comes from lightning-generated H^+ and OH^- ion concentrations that are driven for energy release to opposite lower and upper cloud levels, respectively, by the residual electric field of the thunderstorm. The model consideration is related to recent reports of intracloud flash rate measurements associated with tornadic activity. The required spatial localization of the intracloud-containing flash rate may be a contributing factor to tornadoes being relatively rare occurrences in such storms. Nevertheless, cloud seeding is proposed to alleviate updraft velocity build-ups by promoting "in-situ" recombination of the lightning-generated concentrations of ions.

1. INTRODUCTION

An insignificant role for storm-generated lightning in tornadogenesis had been concluded from earlier scientific debate (Wilkins, 1964; Davies-Jones and Golden, 1975; Watkins et al., 1978; Trapp and Davies-Jones 1997). For example, Grasso and Cotton (1995) have described numerical models for tornadogeneses without cloud electrification parameterizations; and, Spratt et al. (1998) have reported cases of tornado occurrences when little or no lightning occurred at any level. Alternatively, Williams et al. (1999) have reported systematic observations of lightning being a precursor under severe weather conditions to the production of strong ground winds, hail, and tornadic activity. More recently, Buechler et al. (2000) have reported supporting satellite observations of intracloud lightning/tornadic associations. The latter results give support for further investigation of those special characteristics of electrification that might contribute to tornadogenesis.

Here we report on such renewed examination of the electrification basis for tornadic activity being associated with the occurrence of lightning in a severe thunderstorm system. This has involved focusing on the original charged water particle basis proposed by Moore and Vonnegut (1957) and, in greater detail, by Vonnegut (1960), as the key source of significant enhancement of updraft wind velocities potentially leading to tornadic activity. Such model evaluation, that fell short of predicting requisite wind velocities, is now extended in the following report. The results to be described are consistent with the detailed observations reported for intracloud lightning activity by Williams et al. and Buechler et al. From this basis and connection with other observations too, a further aspect of the present investigation, then, was to explore the possibility of interfering at an early stage with the proposed mechanisms supporting tornadic development (Glenn 2001).

2. THE VONNEGUT ELECTRIFICATION MODEL

It is important to begin by mentioning that development of a tornado only under appropriate vertically deflected lateral wind velocity and sufficient vertical thermal gradient is not disputed, rather, the present concern is to investigate whether there is a role for electrification under severe storm conditions. That electrification forces could be involved in tornadogenesis stems from pioneering research done by Vonnegut and colleagues; see, for example, a further updated article by Moore and Vonnegut (1977). Originally, Vonnegut (1960) had concluded that a 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" was required to sustain tornadic action. The updraft velocity has been specified, on previous model and current experimental grounds, as a unique indicator for reaching tornadic development, then growing to hydrodynamic description. Employment of such updraft velocity as a marker is prevalent in the herein referenced articles and in current research investigations whether pro or con for electrification influence. For a horizontal, or vertical, wind velocity of 250 m/s, Vonnegut estimated that ~10^{11} J/s was required to sustain a tornado of the 100 m diameter, appreciably less than the ~10^{15} J available within an average thunderstorm cell. The mechanism by which the tornadic winds were to be generated was by the vertical motion of electrically charged water particles driven by the strong electric field of the thunderstorm.

Vonnegut (1960) provided a sample calculation for charged water particles of 20 micron radius being driven by an electric field, **E** = 300 kV/m, to produce the same force on a cm^3 of air containing 2 g/m^3 of the charged particles as a 20 °C temperature rise. The temperature rise was proposed to be enhanced by subsequent particle condensation. Rathbun (1960) had 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 combine with the negatively-charged ion concentration at the lower cloud level, thus, again producing a temperature rise for updraft enhancement. Through sample calculations for birth of a mini-tornado, Rathbun proposed that a charge density of 10^{10} positive ions/cm^3, taken to be generated within a potential gradient of 2 kV/cm, would 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.

3. THE SUPERCELL DEVELOPMENT

The initial charge generation process responsible for establishment of the global electric field of a thunderstorm supercell has been attributed generally to the collision of ice particles. The latest consensus on the modeled process is that the supercell electrification occurs by a "graupel-ice mechanism" (Rakov and Uman, 2003). The graupel-ice mechanism exhibits a temperature discrimination of the charging process that has been confirmed in a simulated laboratory experiment (Jayaratne et al., 1983). A chemical reaction type equation for the collision mechanism has been given on a conservation of mass and electronic charge basis by Armstrong and Glenn (2005). For example, at relatively higher cloud altitudes, corresponding to lower temperatures, say, in the range of -20 to -24 °C, the mechanism may be described schematically for one collision in a chemical-type van't Hoff reaction isotherm, as

$$(\mathbf{m}\, H_2O)_{graupel} + (\mathbf{n}\, H_2O)_{ice} = \{(\mathbf{m}\, H_2O)\mathbf{p}OH^-\}_{graupel} + \{([\mathbf{n}-\mathbf{p}]\, H_2O)\mathbf{p}H^+\}_{ice} \qquad (1)$$

where **m** is the number of H_2O molecules in a mm- to cm-sized, riming, graupel particle, **n** is the smaller number of H_2O molecules in the colliding smaller sized ice crystal, say, ~10 μm in diameter, and **p** is the number of generated ions of either sign; the mechanism also occurring within a cloud liquid water environment, say, of water content, **L** = 1 g/m^3. Thus, under these conditions in the specified temperature regime, equation (1) applies for the smaller ice crystals being positively charged. With **p** = 1, the equation would apply for the decomposition of a single molecule from a graupel-ice particle collision. A reverse attachment of ions was shown to occur at higher temperatures than -20 °C, thus, being characteristic of collisions at lower altitudes.

The laboratory inference in the demonstrated graupel-ice mechanism is that ice particles and graupel charges build-up by repeated collisions to the measurements able to be made with 10^{-15} Coulomb level sensitivity in both actual and laboratory electrification experiments. The measurements correspond to graupel-ice crystal charge levels, however, involving ~10^4 or more ions. Also, an interesting aspect of the reversed temperature-dependent charging processes is that the lower mass, positively charged ice crystals are created at higher altitudes consistent with the higher main residual supercell pole being electrically positive. In such charge generation processes, a fundamental role is assigned to the already present 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 (Dye et al. 1986; MacGorman and Rust, 1998). Rakov and Uman summarize the situation thusly, "In this mechanism, the electric charges are produced by collisions between graupel and small ice crystals in the presence of water droplets and the large-scale separation of the charged particles is caused by gravity." (Rakov and Uman, 2003).

4. LIGHTNING-SOURCED CHARGE CARRIERS

Recent attention has been drawn to the mysterious aspects of lightning occurrences within a thundercloud (Gurevich and Zybin 2005). In particular, attention was directed to high energy "runaway electrons" being accelerated in the electric field of the thundercloud and, especially relevant to the present consideration, losing energy by ionization of encountered (water) molecules. Such ionization should principally involve production of $OH^-$and H^+ ions from the total concentrations of water molecules. The simplified van't Hoff reaction isotherm for the lightning-based production of singly-charged H_2O decompositions is

$$\mathbf{q}\,(H_2O)_{\mathbf{i}} = \mathbf{q}\, OH^- + \mathbf{q}\, H^+ \qquad (2)$$

where the subscript **i** refers to ionization occurring for either graupel and ice particles as well as individual water particles containing q molecules. Equation (2) accounts in the simplest terms for a new concentration of hydrogen and hydroxyl ions that are generated by the lightning flash and are now to experience influence of the residual electric field of the supercell. The oppositely-charged ion concentrations are respectively driven, along a path centered on the vertical lightning strike, to their opposite poles so as to recombine with the main charges constituting the global electric field. Thus, the OH^- and H^+ charges are driven in opposite up-and-down directions, respectively. Such dual hydrogen and hydroxyl ion fluxes are the counterpart action to Rathbun's description for H^+ motion in a cloud-to-ground lightning strike. Even so, the energy released in the lightning strike is small compared to the energy stored in the supercell.

5. DUAL MECHANISMS OF UPDRAFT ENHANCEMENT

The lightning-sourced H^+ ions are driven downward within the intracloud chamber to recombine with the main particle-attached OH^- charge concentration of the lower cloud structure, and vice versa for the lightning-sourced OH^- ion concentration. A schematic description of the mechanism for energy gained by the lightning-spawned and downward-driven H^+ ions is given in a single van't Hoff equation form relating to equation (1) as

$$\mathbf{q}\,H^+ + \{(\mathbf{m}\,H_2O)\mathbf{p}OH^-\}_{graupel} = \{([\mathbf{m}+\mathbf{q}]\,H_2O)[\mathbf{p}-\mathbf{q}]OH^-\}_{graupel} \qquad (3)$$

in which a summed exothermic energy is liberated both in ion recombination and ice or water transformation at the lower cloud level. The ionic recombination energy, is ~ 20 times greater than the condensation energy to water. Only immediate recombination on site or at higher altitude of the lightning-generated ions will reduce this thermal driving force from having its main influence on updraft wind velocity enhancement at the lower cloud level.

The hydrogen ions have negligible cross-sections and therefore produce an insignificant influence of any downward directed collisional influence or momentum exchange with air mass. On the other hand, the more massive and relatively, very substantially-sized, hydroxyl ions, that are driven in the counterpart upward direction by the same electric field are proposed to add a substantial pressure in that direction as they sweep all in their way to the upper cloud level. At that level, they react in accordance with a reversed-charge assignment in equation (1) as

$$\mathbf{q}\,OH^- + \{([\mathbf{n}-\mathbf{p}]\,H_2O)\mathbf{p}H^+\}_{ice} = \{([\mathbf{n}-\mathbf{p}+\mathbf{q}]\,H_2O)[\mathbf{p}-\mathbf{q}]H^+\}_{ice} \qquad (4)$$

At the upper cloud level, the thermal effect of such liberated recombination energy is easily tolerated at the lower existent temperatures whereas in process of arrival the electric-field-driven hydroxyl ion flux delivers an additional upward pressure influence for wind velocity enhancement, much more so than had been attributed by Rathbun (1960) to the reverse case of neutral air collisions from upward directed hydrogen ions produced by cloud-to-ground lightning strikes. Thus, the respectively oppositely charged intracloud ions caused by lightning each contribute in their own way to enhancing the updraft wind velocity.

6. 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. On this basis, he derived the relationship for the electric force, **F**, on such particles as:

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

where **E** is the electric field, **L** is the liquid water content (mentioned earlier in connection with the graupel-ice mechanism), and **a** is the charged water particle radius. For **E** = 10 ESU/cm (= 3 kV/cm), **L** = 2 g/m^3, and **a** = 20 μm, a relatively small force of 0.07 dynes (= 0.7 μN) was found to act on a cubic cm of the cloud. The force was estimated to produce a somewhat disappointing equivalent updraft of a temperature rise of ~20 °C.

Figure 1 is a key presentation of the electric force associated with differently charged ion and water/ice/graupel sizes, incorporating the relationship derived by Vonnegut. The closed circle point applies for Vonnegut's reported **F** = 7 x 10^{-7} N and **a** = 2 x 10^{-5} m (20 μm) chosen as a representative water droplet size (consistent with the described laboratory experiment for the graupel-ice mechanism). The inverse dependence of **F** on **a,** obtained in the Vonnegut relation of equation (5), is shown to be extended from the specified closed circle point in Figure 1 both to smaller particle and larger graupel sizes, say, in the latter case, between 2 mm and 5 cm, that are encountered in tornado-producing supercells. Negligible electrical forces act on the graupel. Dashed Vonnegut lines for larger or smaller values of **L** are drawn parallel to the solid line.

The electrical force, **F**, acting on either species of a fully ionized concentration, **L**, in g/m^3 of water, is obtained analogously to the derivation of equation

(5) by multiplying **E** by the total effective charge **Q** = **q** (**N L** / 18), thus,

$$\mathbf{F} = \mathbf{E}\,\mathbf{q}\,(\mathbf{N}\,\mathbf{L} / 18) \qquad (6)$$

in which **q** is the electron charge, 1.6 x 10^{-19} C, and **N** is Avogadro's number, 6.02 x 10^{23} of molecules contained in 18 grams of water. The fraction **L**/18 is the proportional mass of water molecules in **L**. For 100% ionization of **L**, the filled square point is obtained in Figure 1 at **F** = 3.2 x 10^3 N corresponding to **a** = 0.96 x 10^{-10} m for the OH^- bond length. At 0.1% ionization of **L**, say, accomplished by immediate recombination of the ions, the filled square point is correspondingly shifted downward. The same electrical force would be obtained for the counterpart lightning-generated H^+ concentration and could be plotted to the left in Figure 1, possibly, at the effective physical size of the proton radius of 1.44 x 10^{-15} m.

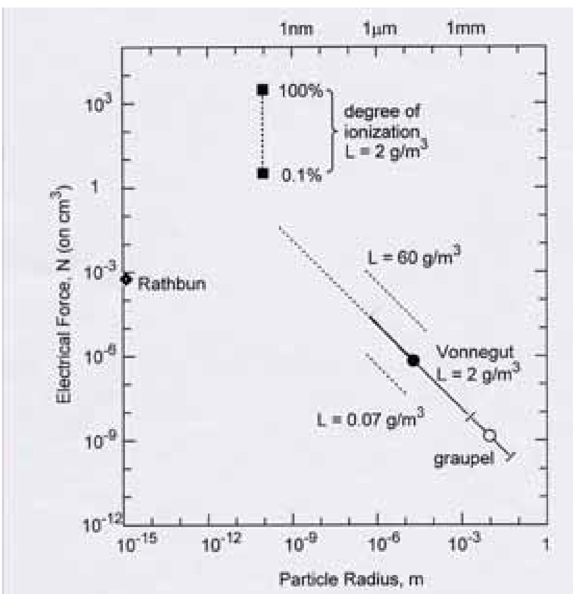

Figure 1. Electric force versus H^+ and OH^- ionic radii and charged water droplet and charged graupel radii

The downward acceleration of the lightning-sourced H^+ concentration would be enhanced relative to the OH^- acceleration by a factor given by the seventeen times ratio factor of the hydroxyl-to-hydrogen ion masses. Instead of plotting in Figure 1 the shifted **F**-**a** point for the H^+ ions, the value of **F** is plotted as a filled triangle that applies for the 10^{10} H^+ 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. Thus, compared to both Rathbun and Vonnegut evaluations, Figure 1 demonstrates that orders of magnitude greater electric forces apply for lightning-generated ion populations under the same conditions previously considered for the two other situations.

7. DISCUSSION

MacGorman and Rust (1998) had reported that both total and intracloud flash rates were large in tornadic supercell storms at the time of tornado occurrences (see also Rakov and Uman, 2003). Both Williams et al. (1999) and Buechler et al. (2000) reported far greater intracloud, as compared with below cloud, flash rates preceding tornadogenesis. In fact, Williams et al. reported "jumps" in intracloud lightning flash rates of 3 to 8/s that were associated with sudden increases in wind velocities of 50 to 70 mph at ground level, and, very significantly, 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 gives evidence for considering that the reverse situation applies, that is, whatever the current level of updraft in a severe storm, if a sudden increase in intracloud lightning flash rate occurs, and it is of sufficiently high level, then, a very significant generation of hydroxyl and hydrogen ions occurs. The hydrogen ions are driven faster to reaction at the lower cloud level, and thereby, produce an additional lower cloud thermal influence to the updraft, one that to the authors' knowledge has not been considered previously. The much larger OH^- ions, in turn, push upwards, producing a rising pressure influence to the updraft. Both actions add to enhancement of the wind updraft.

The need for repeated lightning strikes provides an additional spatial requirement if they are to build from an embryonic mini-tornado. By analogy with screw dislocation behavior in solid mechanics, such mini-vortices repel each other when having the same rotation vectors and annihilate each other if having the same sign rotations. Thus, the only mechanism by which truly high wind velocities might build to tornadic condition through the added influence of electrification, as considered here, is if the repeated lightning strikes occur within the spatially localized "core" of the vortex. The requirement is proposed to be a contributing factor to the observation that tornadoes are a relatively rare outcome even of severe weather dissipations.

Lastly, there is the issue of how the tendency towards tornadogenesis under severe storm electrification conditions might be modified according to the present model interpretation so as to prevent build-up to tornadic activity. A particular version of cloud seeding provides a possible solution. The aim would be either to interfere with the needed spatially localized lightning flash rate or to promote recombination of the lightning-sourced H^+ and OH^- concentrations as near as possible to the localized regions of generation. In both cases, selective cloud seeding actions might be useful. For example, conductive material particles or ribbon segments might be employed to beneficially influence the areal spread of the flash rate. Cloud seeding of lighter-than-air, neutral or charged, nanoparticles might be employed to effect "in-situ" recombination of the lightning-sourced concentration of ions. The employment, for example, of suitable fly-ash-like particles would have significant lifetimes for effecting such recombinations and, with pre-imposed negative charges, could be directed just above the lower cloud level to preferentially combine with the relatively more influential H^+ concentration.

8. SUMMARY AND CONCLUSIONS

New consideration of a role for severe thunderstorm electrification in tornadogenesis is described for such event occurring within the intracloud environment and is shown to constructively relate to the preceding pioneering researches of Vonnegut and colleagues. Lightning-sourced H^+ and OH^- particles are more driven than charged water particles by the thunderstorm electric field and add 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 relatively small-sized water droplets. The hydrogen ions are driven downwards to recombine at the lower cloud level with the resident main concentration of hydroxyl ions, presumably, particle-captured, and through ionic recombination add significant thermal influence to the updraft. The lightning-generated hydroxyl ions are driven upwards to effect significant sweeping action on the various air particles in the intracloud chamber. Repeated lightning strikes, however, are required to be spatially localized within an established vortex "core" in order to lead to tornadic activity. The flash rate requirement is in line with recent experimental observations associating severe wind velocity build-ups; and, the required spatial localization of the "lightning rate jumps" is in line with tornadoes being relatively rare occurrences.

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