Exploring a physically based tool for lightning cessation: Preliminary results

Elise V. Schultz[1], Walter A. Petersen[2], Lawrence D. Carey[1]

[1]Univ. of Alabama, Huntsville, AL
[2]NASA/MSFC, Huntsville, AL

Abstract

NASA's Marshall Space Flight Center (MSFC) and the University of Alabama in Huntsville (UAHuntsville) are collaborating with the 45th Weather Squadron (45WS) at Cape Canaveral Air Force Station (CCAFS) to enable improved nowcasting of lightning cessation. This project centers on use of dual-polarimetric radar capabilities, and in particular, the new C-band dual-polarimetric weather radar acquired by the 45WS. Special emphasis is placed on the development of a physically based operational algorithm to predict lightning cessation.

While previous studies have developed statistically based lightning cessation algorithms, we believe that dual-polarimetric radar variables offer the possibility to improve existing algorithms through the inclusion of physically meaningful trends reflecting interactions between in-cloud electric fields and microphysics. Specifically, decades of polarimetric radar research using propagation differential phase has demonstrated the presence of distinct phase and ice crystal alignment signatures in the presence of strong electric fields associated with lightning. One question yet to be addressed is: To what extent can these ice-crystal alignment signatures be used to nowcast the cessation of lightning activity in a given storm? Accordingly, data from the UAHuntsville Advanced Radar for Meteorological and Operational Research (ARMOR) along with the NASA-MSFC North Alabama Lightning Mapping Array are used in this study to investigate the radar signatures present before and after lightning cessation. A summary of preliminary results is presented.

Thus far our case study results suggest that the negative differential phase shift signature weakens and disappears *after* the analyzed storms ceased lightning production (i.e., after the last lightning flash occurred). This is a key observation because it suggests that while strong electric fields may still have been present, the lightning cessation signature was encompassed in the period of the polarimetric negative phase shift signature.

To the extent this behavior is repeatable in other cases, even if only in a substantial fraction of those cases, the analysis suggests that differential propagation phase may prove to be a useful parameter for future lightning cessation algorithms.

Indeed, preliminary analysis has shown additional indications of the weakening and disappearance of this ice alignment signature with lightning cessation. A summary of these case-study results is presented.

Introduction

Many lightning studies have investigated methods of forecasting lightning initiation but very few have tackled the challenge of lightning cessation. Studies that have approached lightning cessation have looked at the issue qualitatively. Stano et al. (2010) completed a comprehensive statistically based study on lightning cessation using the Lightning Detection and Ranging (LDAR) network at Kennedy Space Center (KSC). The study investigated a variety of statistical methods and the result provided additional confidence for the 45WS lightning launch commit criteria (LLCC).

Other previous studies have used conventional radar methods to determine a storm's potential for lightning. Bateman et al. (2003), compared radar reflectivity to electric field mill data from the Airborne Field Mill (ABFM) Project to compute a volume averaged height integrated radar reflectivity (VAHIRR) product. VAHIRR serves as a proxy for the electric field in non-convective clouds in order to assist in the evaluation of the anvil cloud LLCC. It provides a metric to determine if the current electric field is strong enough to support lightning or could lead to rocket triggered lightning. Wolf (2007) studied cloud-to-ground (CG) lightning data alongside radar reflectivity to determine when an imminent threat for CG lightning exists. Wolf's results were similar to past studies where the lightning threat is increase (decreases) once the 40 dBZ height is roughly 3.1-3.5 km above (below) the ambient environment -10°C layer.

Polarimetric radar studies have provided valuable knowledge in lightning research through the identification of ice crystal orientation (e.g. McCormick and Hendry, 1975; Hendry and McCormick 1976; Hendry and Antar 1982; Krehbiel et al. 1991, 1992, 1996; Metcalf 1995; Metcalf et al, 1993; Caylor and Chandrasekar 1996; Scott et al. 2001; Marshall et al. 2009). These studies have used changes in various polarimetric measurements to infer ice crystal orientation.

Ice crystal orientation is the result of a balance between aerodynamic and electrical forces present within the cloud. (Weinheimer and Few, 1987) Aerodynamic forces include gravity and drag as well as account for storm kinematics and also depend on hydrometeor size and shape. For example (Figure 1), if a vertical electric field is stronger than the aerodynamic force in the mixed phased region of a thunderstorm then ice crystals will likely become vertical, aligning with the electric field. However, if the aerodynamic force dominates the electric field than the ice crystal would remain horizontally aligned.

By connecting the physics behind ice crystal orientation discussed in Weinheimer and Few (1987) with polarimetric radar observations, we can show that ice crystal signatures provide a physical indicator of lightning potential within a thunderstorm (Krehbiel et al. 1993). As the electric field builds up, particles become more and more vertically aligned with the electric field. When lightning occurs, the field “relaxes” and the particles abruptly change back to horizontal alignment.

Data and Methodology

This project centers on the use of dual-polarimetric radar capabilities, and in particular, the new C-band dual-polarimetric weather radar acquired by the 45WS. However, since the 45WS C-band radar is not operational at this time, data from the UAHuntsville Advanced Radar for Meteorological and Operational Research (ARMOR) along with the North Alabama Lightning Mapping Array (NALMA) are used to investigate the radar signatures present before and after lightning cessation. The ARMOR radar is a dual-Polarimetric, C-band radar similar to the new 45 WS radar. ARMOR is located at the Huntsville International Airport and runs 24 a day in default mode with special scanning capabilities available for research mode operations. Figure 2 shows the locations of ARMOR, NALMA, and the WSR-88D (KHTX) in northern Alabama.

This study is currently focused on the benefits of using two of the polarimetric variables from ARMOR: differential propagation phase (PHIDP) and specific differential phase (KDP). PHIDP (ϕ_{DP}) is the difference of the horizontal and vertical phase shift of the electromagnetic wave.

$$\phi_{DP} = \phi_{HH} - \phi_{VV}$$

When the radar beam encounters hydrometeors with a larger horizontal axis (relative to the vertical), the radar beam becomes attenuated and the phase is shifted more in the horizontal than the vertical since the refraction of water is more than that of air. Therefore, PHIDP increases. The opposite is true when the radar beam encounters hydrometeors with a larger vertical axis; PHIDP decreases in range. Figure 3 shows an example of both a negative and positive phase shift in PHIDP. If we take the range derivative of PHIDP, we get the calculation for KDP.

$$KDP = \frac{\phi_{DP}(r_2) - \phi_{DP}(r_1)}{2(r_2 - r_1)}$$

KDP will visually direct the eye to areas of increasing PHIDP (positive KDP) or decreasing PHIDP (negative KDP) as seen in Figure 4.

Identifying ice crystal signatures involves both the use of ARMOR and NALMA data. First, suitably scanned (encompassing the charging layer of -10 to -40°C) storms with lightning cessation within our domain (within 125 km of ARMOR) must be identified. In fact, it is desirable to have the storms fall within the observational domain for a period of time prior to and after cessation in order to accurately document the changes in PHIDP as lightning ceases. With the lightning and radar data combined, initial visual analysis is performed to identify areas of decreasing PHIDP in relation to the time of the last lightning flash within a particular storm.

In order to create an operational tool to better predict lightning cessation, this process must be automated. KDP can serve as a substitute for the visual analysis of PHIDP because it defines the sought after gradient by definition. Typical uses of KDP are for rainrate estimations therefore the spatial smoothing is rather fine, on the order of a couple kilometers. However, for the lightning cessation application, we are experimenting with the use of a more coarse range resolution, or a smoother KDP field to aide in easier phase shift identification over storm or anvil scales and the resultant additional filtering of noise intrinsic to the KDP variable. The KDP calculation currently being evaluated was created by applying the Hubbert FIR filter (Hubbert and Bringi, 1995) to the corrected PHIDP and then averaging the PHIDP over a distance of 41 range gates or 5.125 km (one gate is 125 m). We are still exploring improvements to this KDP smoothing calculation for lightning cessation applications. With further investigation, we will determine if additional variables such as differential reflectivity (ZDR) or temperature and reflectivity thresholds will provide additional information to a lightning cessation prediction tool.

Preliminary Results

From an analysis of the case presented in Figures 3, 4, and 5, we found that the negative phase shift signature weakened and disappeared *after* the storm ceased lightning production (i.e., after the last lightning flash occurred). Figure 5 displays the evolution of KDP through mean KDP profiles for 3 minutes prior and 4, 20, and 37 minutes following the last flash. This evolution is a key observation because it suggests that while strong electric fields may still have been present, the lightning cessation signature was encompassed in the period of the polarimetric negative phase shift signature. To the extent this behavior is repeatable in other cases, even if only in a substantial fraction of those cases, the analysis suggests that PHIDP and KDP may prove to be useful parameters for future lightning cessation algorithms. Indeed, a preliminary analysis of 10+ cases has shown additional indications of the weakening and disappearance of this ice alignment signature with lightning cessation.

Summary

While our preliminary results are promising and agree with our conceptual model (Figure 1), we must complete the connection between observations and the physics behind ice crystal orientation through the help of modeling the radar scattering response. Figure 5 illustrates the interplay between observations and physics with the T-matrix and Mueller Matrix. Through the help of these models, we can have further build our confidence in using radar observations to infer lightning cessation.

Finally, assuming a robust methodology for scanning a given thunderstorm to identify the cessation stage could be found, we must also identify different approaches to using the phase signature (e.g., as is, a vertical or radial integration etc.) and subsequently quantify them in order to provide a more objective foundation for the development of a lightning cessation algorithm. Other pieces of relevant information (e.g., the VAHIRR behavior or trends in VAHIRR, the lightning trend itself) must also be identified that can be combined to make such an algorithm feasible for use in operations.

Acknowledgements

This research is made possible by funding support provided by NASA MSFC as a component of the Shuttle program.

References

Bateman, M., and Coauthors, 2005: Comparison of in-situ electric field and radar derived parameters for stratiform clouds in central Florida. *1st Conf. Meteor. Appl. Lightning Data, San Diego, CA,* P1.10.

Caylor, I. J., and V. Chandrasekar, 1996: Time-varying ice crystal orientation in thunderstorms observed with multiparameter radar. *IEEE Trans. Geosci. Remote Sensing.* **34,** 847-858.

Hendry, A. and G. C. McCormick, 1976: Radar observations of the alignment of precipitation particles by electrostatic fields in thunderstorms. *J. Geophys. Res.,* **81,** 5353-5357.

Hendry, A., and Y. M. M. Antar, 1982: Radar observations of polarization characteristics and lightning-induced realignment of atmospheric ice crystals. Radio Sci., **17,** 1243-1250.

Hubbert, J., and V. N. Bringi, 1995: An iterative filtering technique for the analysis of copolar differential phase and dual-frequency radar measurements. *J. Atmos. Oceanic Technol.,* **12,** 643-648.

Krehbiel, P. R., W. Rison, S. McCrary, T. Blackman, and M. Brook, 1991:Dual-polarization radr observations of lightning echoes and precipitation alignment at 3 cm wavelength. *25th Int. conf. Radar Meteor., Amer. Meteor. Soc.,* 901-904.

Krehbiel, P. R., T. Chen, S. McCrary, W. Rison, G. Gray, and T. Blackman, 1992: Dual-polarization radar signatures of the potential for lightning in electrified storms. *9th Int. Conf. Atmos. Elect., St. Petersburg, Russia,* 166-169.

Krehbiel, P. R., T. Chen, S. McCrary, W. Rison, G. Gray, and M. Brook, 1993: “Dual-polarization radar indications of the potential for lightning in storms near Kennedy Space Center, Florida. 26th Conf. Radar Meteor., *Amer. Meteor. Soc.,* 309-311.

Krehbiel, P. R., T. Chen, S. McCrary, W. Rison, G. Gray, and M. Brook, 1996: The use of dual channel circular-polarization radar observations for remotely sensing storm electrification. *Meteor. Atmos. Phys.,* **58,** 65-82.

Marshall, T. C., M. Stolzenburg, P. R. Krehbiel, N. R. Lund, and C. R. Maggio, 2009: Electrical evolution during the decay stage of New Mexico thunderstorms. J. Geophys. Res., 114, D02209, doi:10.1029/2008JD010637

McCormick, G. C. and A. Hendry, 1975: Principles for the radar determination of the polarization properties of precipitation. *Radio Sci.,* **10,** 421-434.

Metcalf, J. I., 1995: Radar observations of changing orientations of hydrometeors in thunderstorms. *J. Appl. Meteor.,* **34,** 757-772.

Scott, R. D., P. R. Krehbiel, and W. Rison, 2001: The use of simultaneous horizontal and vertical transmissions for dual-polarimetric radar meteorological observations. *J. Atmos. Oceanic Technol.,* **18,** 629-648.

Stano, G. T., H. E. Fuelberg, W. P. Roeder, 2009: Developing empirical lightning cessation forecast guidance for the Kennedy Space Center. J. Geophys. Res., 115, DO9205, doi:10.1029/2009JD013034

Weinheimer, A. J., and A. A. Few, 1987: The electrical field alignment of ice particles in thunderstorms. *J. Geophys. Res.,* **92,** 14,833-14,844.

Wolf, P., 2007: Anticipating the Initiation, cessation, and frequency of cloud-to-ground lightning, utilizing WSR-88D Reflectivity Data. *Electronic Journal of Operational Meteorology.*

Figures

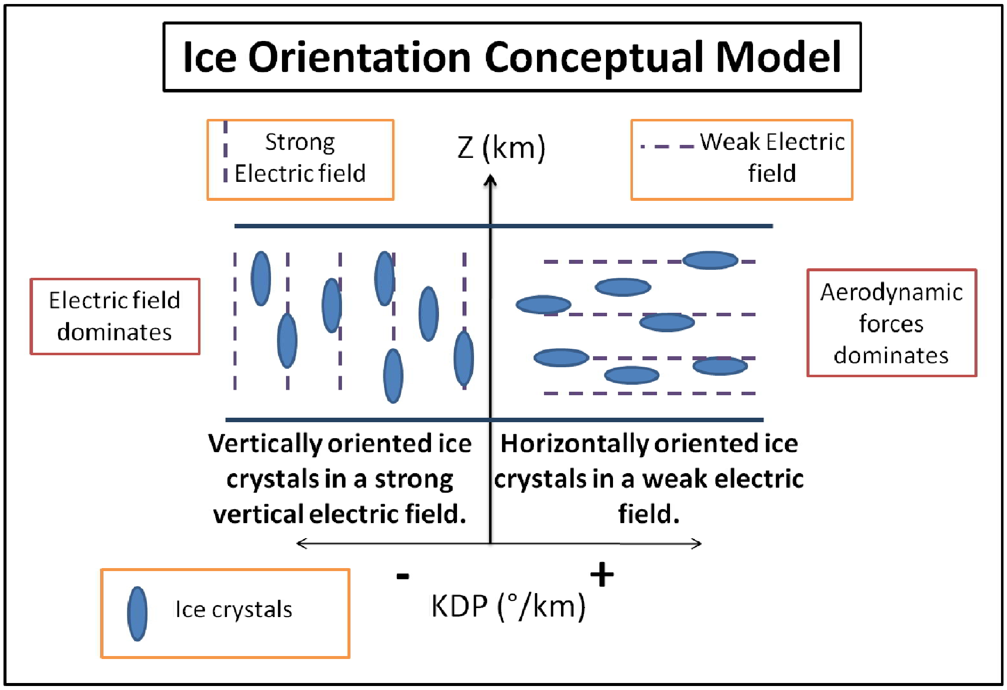

Figure 1 - Conceptual model of ice orientation's dependence on electric and aerodynamic forces. When the electric field dominates the aerodynamic force, ice crystals will align with the electric field. When the electric field is weaker the particles will align horizontally.

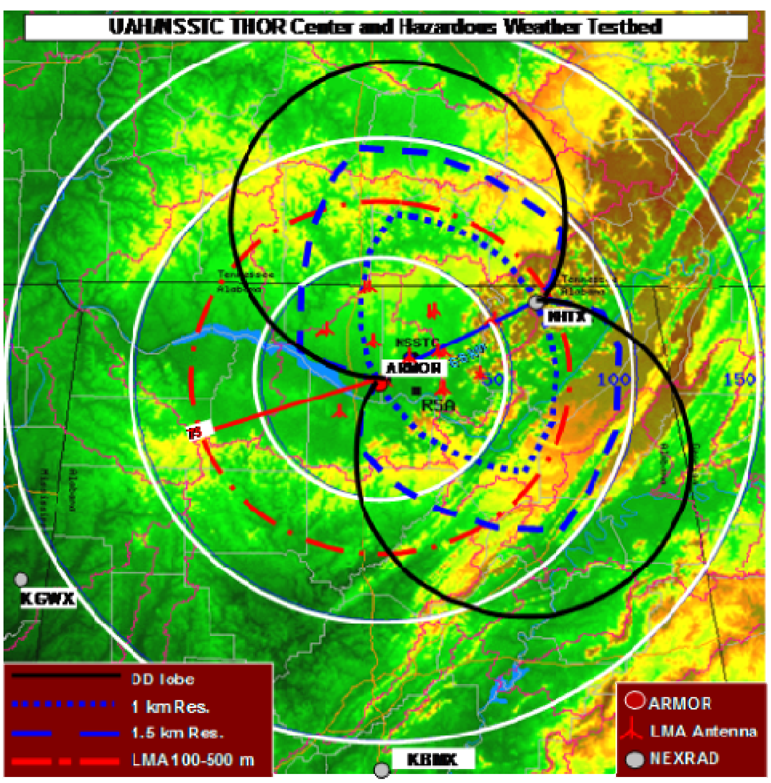

Figure 2 – Locations of ARMOR, KHTX, and the NALMA in Northern Alabama.

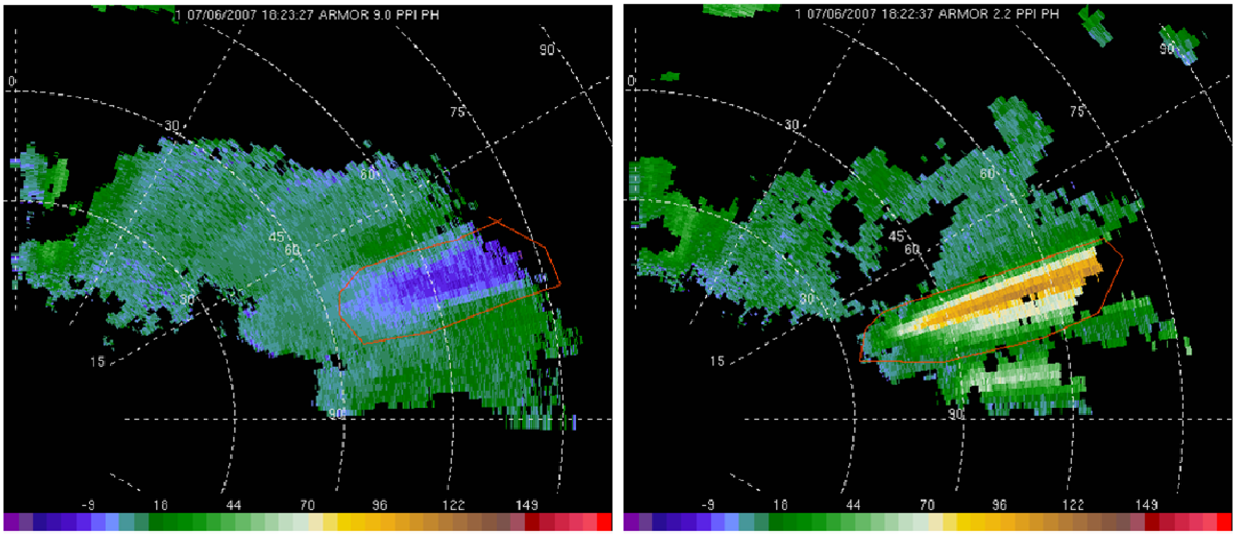

Figure 3 - Negative (left) and positive (right) shifts (outlined in red) in the differential phase (PHIDP) parameter. The negative phase shift (at 9.0° elevation scan) indicates that there is more attenuation in the vertical polarization than the horizontal. At 60 km from the radar (approximately center of the area outlined in red), the radar beam is around 9.5 km above the ground thus the hydrometeors that are sampled here are likely ice. The positive phase shift shown is a 2.2° elevation scan. The center of the area outlined in red is approximately 2.5 km in height. The freezing level for this case is 4.6 km therefore at a height of 2.5 km the radar is sampling liquid hydrometeors.

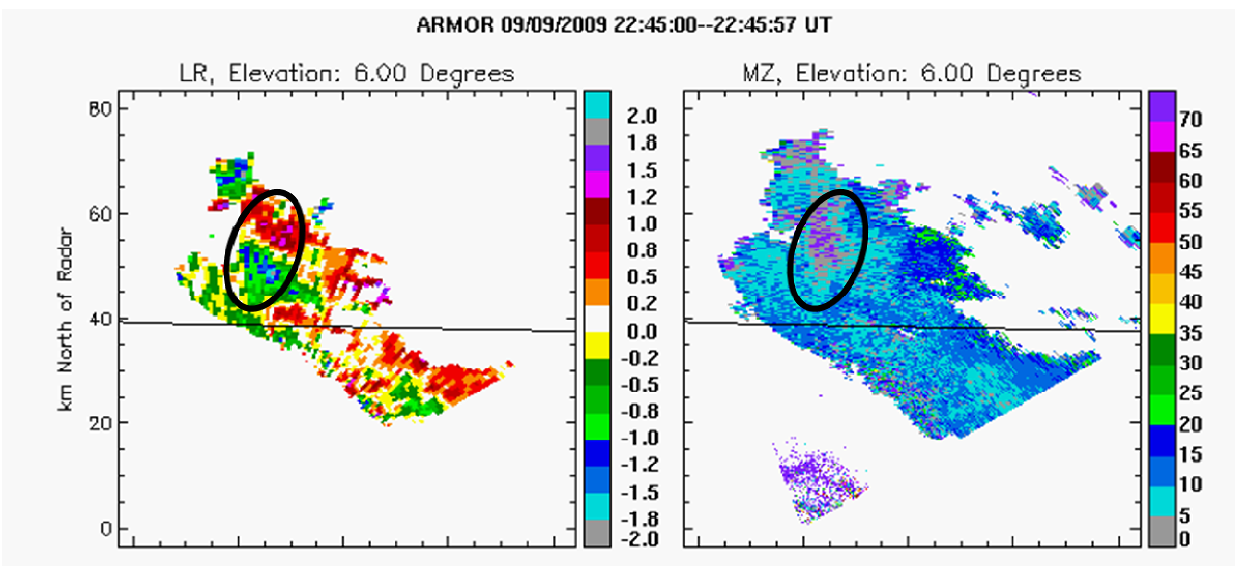

Figure 4 – KDP calculated from filtered PHIDP smoothed over a range of 41 gates (left) and raw PHIDP (right). The black ovals show an area of a negative phase shift. KDP values below 0 indicate vertically aligned particles. The hydrometeors towards the front and middle of the outlined area are likely more vertically aligned than the particles further away from the radar. Increasing magnitudes of negative KDP values likely indicate more vertically aligned particles.

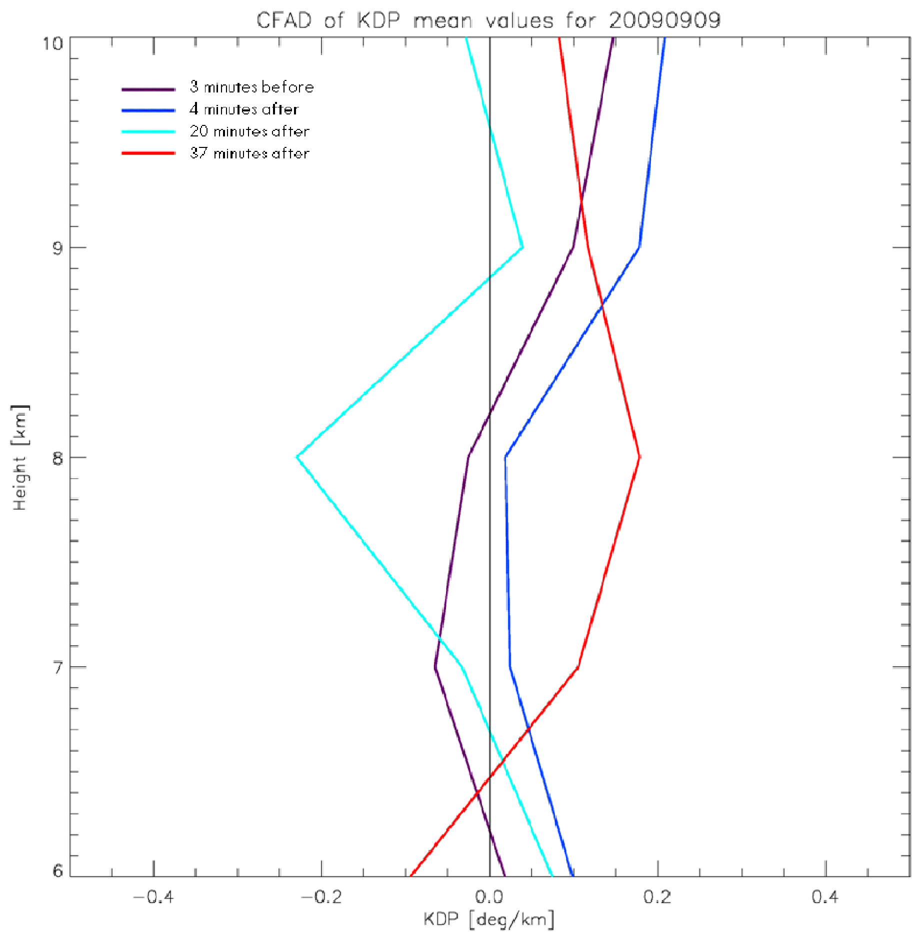

Figure 5 - Mean KDP time-series with height. The times selected represent a profile 3 minutes prior and 4, 20, and 37 minutes after the last flash within the selected storm. These profiles illustrate what is hypothesized based on previous studies.

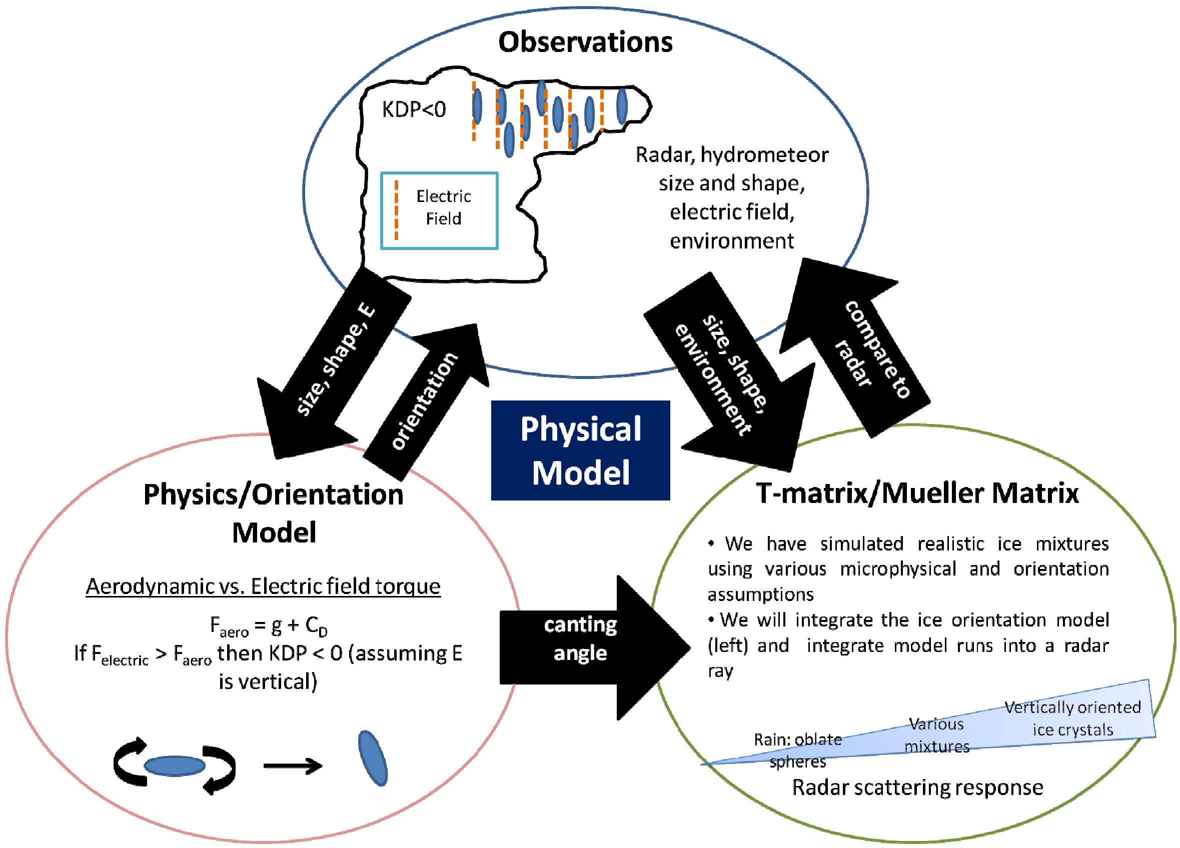

Figure 6 - This diagram shows the interconnectivity of radar observations, orientation physics, and modeling the orientation of ice crystals to demonstrate the validity of using radar observations to determine lightning cessation.