Kinematic and Microphysical Control of Lightning in Multicell Convection over Alabama during DC3

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Abstract— Analysis of five long lived multicell convective complexes observed over northern Alabama demonstrated that radar kinematic (maximum updraft, convective updraft volume) and microphysical (graupel echo volume, graupel mass, 30 dBZ echo volume) observables in the charging zone (-10 °C to -40 °C layer) are qualitatively correlated to the observed total flash rate. Specific linear equations were developed and tested from this Alabama data set to estimate total flash rate from these radar observables. Among the radar observables tested, graupel echo volume provided the most robust and accurate estimate of total flash rate for all Alabama cells, closely followed by the graupel mass. Based on this limited data set, it appears that a total flash rate can be reasonably estimated by simply knowing the volume of cloud containing graupel in the charging zone.

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Keywords—Flash rate parameterizations, polarimetric radar, dual-Doppler radar, lightning NO_x

I. INTRODUCTION

The Deep Convective Clouds and Chemistry (DC3) experiment [Barth et al. 2013] seeks to examine the relationship between deep convection and the production of nitrogen oxides (NO_x) via lightning (LNO_x). A critical step in estimating LNO_x production in a cloud-resolving model (CRM) without explicit lightning is to estimate the flash rate from available model parameters that are statistically and physically correlated [Pickering et al. 1998; Barthe and Barth 2008; Barthe et al. 2010]. As such, the goal of this study is to develop, improve and evaluate lightning flash rate parameterizations using DC3 radar and lightning mapping array (LMA) observations over northern Alabama. A related goal of this study is to investigate the kinematic and microphysical control of general lightning properties in multicell convection. In addition to flash rate, the lightning type (intra-cloud [IC] vs. cloud-to-ground [CG]) and flash extent are documented and related to polarimetric and dual-Doppler derived radar properties. These radar-lightning relationships may form the basis of new parameterizations that could improve estimates of LNOx production in CRM simulations of multicell thunderstorms.

II. BACKGROUND

Based on numerous laboratory [e.g., Takahashi et al. 1978; Saunders 1994; Saunders and Peck 1998] and observational [Dye et al. 1986; 1989] studies, the primary means for particle charging in thunderstorms is thought to be the non-inductive mechanism (NIC), which involves rebounding collisions between graupel and small ice crystals in the presence of supercooled water. Particle fall speed differences and convective motions in a vigorous updraft result in storm scale charge separation, strong electric fields sufficient for breakdown and lightning.

Because of its ability to identify and quantify graupel and convective updrafts, dual-polarization/Doppler radar has been used to study the microphysical and kinematic control of lightning flash rate [e.g., Carey and Rutledge 1996; 2000; Wiens et al. 2005]. In these studies, graupel amount (e.g., graupel echo volume or precipitation ice mass) and updraft strength (e.g., maximum updraft, updraft volume) were shown to be highly correlated to the total (IC+CG) lightning flash rate. Based on a sample of 11 storms from Colorado and Alabama, Wiebke et al. [2008] and Wiebke and Petersen [2008] used similar radar observations to derive specific quantitative relationships between the total flash rate and the graupel (or precipitation ice) mass, ice flux and updraft volume. These empirical relationships along with earlier ones based on the ice water path [Petersen et al. 2005] and the maximum updraft [Pickering et al. 1998] form the WRF-Chem total flash rate parameterization scheme that is currently used for LNO_x studies [Barthe et al. 2010; Cummings et al. 2014].

Since the current WRF-Chem total flash rate parameterization scheme is based on a limited number of observations, the purpose of this study is to develop, improve and evaluate lightning flash rate parameterizations using DC3 radar and total lightning observations over northern Alabama. Similar studies are underway for storms observed during DC3 over Colorado (Basarab et al. 2013) and Oklahoma/Texas in order to increase the sample size and provide variation in storm type and environment, thus resulting in a more robust flash rate parameterization scheme.



Fig. 1. A map of the DC3 Alabama domain. The green triangles represent NA LMA VHF antennas. The solid red dot represents the location of the ARMOR radar. The solid blue dot represents the location of KHTX. The short-dashed lines represent regions where multi-Doppler wind synthesis can be performed.

III. DATA

DC3 took place in May - June 2012 over Northern and two other locations (Colorado Alabama and Oklahoma/Texas) [Barth et al. 2013]. For DC3 Alabama, the Advanced Radar for Meteorological and Operational Research (ARMOR) (Petersen et al. 2005) and the Weather Surveillance Radar - 1988 Doppler (WSR-88D) comprises the dual-Doppler and dual-polarization radar network (Fig. 1). The S-band WSR-88D is operated and owned by the National Weather Service (NWS) and is located at Hytop, AL (KHTX). The Cband ARMOR radar is located at the Huntsville International Airport and is co-owned by the University of Alabama in Huntsville (UAH) and WHNT. ARMOR and KHTX have a beamwidth of 1° and .92°, respectively, and both operate in a simultaneous transmit and receive of both the horizontal and vertical channels. ARMOR and KHTX are both capable of measuring horizontal reflectivity (Z_h) , Doppler velocity (V_r) , differential reflectivity (Z_{dr}), the co-polar correlation coefficient (ρ_{hv}) and differential phase (Φ_{dp}). The specific differential phase (K_{dp}) for ARMOR is computed using a method that is outlined in Bringi and Chandrasekar (2001). Additional specifications of ARMOR are discussed in Petersen et al. (2005). The relatively close proximity of ARMOR and KHTX (approximately 70 km) presents the opportunity for three dimensional wind retrievals within the highlighted areas denoted in Fig. 1.

Case selections were primarily dictated by the proximity of convection to both the aforementioned multi-Doppler region as well as the proximity to the center of the northern Alabama Lightning Mapping Array (NA LMA) [Goodman et al. 2005], which is located within the dual-Doppler network (Fig. 1). NA LMA is owned and operated by the National Aeronautics and Space Administration-Marshall Space Flight Center (NASA MSFC). The network consists of 11 very high frequency (VHF) antennas across northern AL that detect radiation emissions from propagating leaders associated with lightning using a time-of-arrival technique [Goodman et al. 2005]. The NA-LMA in conjunction with Vaisala's National Lightning Detection Network (NLDN) allow for a detailed depiction of total lightning.

IV. METHODOLOGY

Both ARMOR and KHTX radar data underwent a vigorous quality control process implemented at UAH. As a result of ARMOR's relatively shorter wave length (relative to KHTX), propagation effects occur with the presence of heavy rain. To address this issue, all raw ARMOR data were corrected for attenuation and differential attenuation using a self-consistency method outlined in Bringi et al. [2001]. The corrected ARMOR and raw KHTX radar data were then manually inspected using the National Center for Atmospheric Research's (NCAR) SOLO radar visualization and editing software. During this labor-intensive process, aliased Doppler velocities were corrected and spurious echoes associated with second trip echoes, ground targets and anomalous propagation were removed. In the event that ARMOR operations consisted of sector volumes, an internal method for correcting any azimuth pointing angle error was employed.

Radiosonde observations (RAOBs) from the UAH mobile ballooning facility were quality controlled by specialists at NCAR using the techniques outlined in Loehrer et al. [1996]. The combination of temperature data and the polarimetric radar variables from ARMOR allowed for the use of a fuzzy logic based particle identification algorithm, hereafter NCAR PID [Vivekanandan et al. 1999; Straka et al. 2000]. While originally developed for use at S-Band, modifications to the NCAR PID [Deierling et al. 2008] were necessary owing to both ARMOR's C-band wavelength and operational mode (simultaneous transmit of H and V results in the inability to attain the linear depolarization ratio [LDR]). With information from NCAR PID, several microphysical quantities thought to be relevant for the NIC mechanism (e.g., graupel echo volume, graupel mass) can be computed.

Once the quality control of ARMOR and KHTX data was completed, both sets of data were gridded using NCAR's REORDER package [Mohr et al. 1986]. Polarimetric and Doppler radar quantities (excluding NCAR PID data) were gridded from radar space to a Cartesian grid with spacing of 1 km in x, y and z using the Cressman Weighting scheme [Cressman 1959] and radii of influence of 1 km in the horizontal and vertical. The NCAR PID information was also gridded to Cartesian space with 1 km grid spacing in the horizontal and vertical dimensions using a Nearest Neighbor Weighting scheme and similar radii of influence. For this study, graupel volume and graupel mass were computed. Consideration was only given to regions between the -10 °C and -40 °C layer. This so-called "charging region", as termed by Latham et al. [2004], is theorized to be the region in which active NIC of graupel primarily occurs. The number of grid boxes associated with graupel particles identified by the NCAR PID were summed over the height layer corresponding to the -10 °C and -40 °C temperature layer and then multiplied by the grid box volume to attain the desired graupel echo volume. For grid boxes identified as containing graupel by the NCAR PID in the same height layer, an estimate of graupel mass was obtained from a reflectivity - ice mass (Z-M) relationship found in Carey and Rutledge [2000], which is based on the Rayleigh scattering approximation for an assumed exponential ice particle size distribution.

NA LMA Total	5/18/2012 Cell A1	5/21/2012 Cell B1	5/21/2012 Cell B2	6/11/2012 Cell C1	6/14/2012 Cell D1
Lightning Property					
Mean	6.5	0.3	1.1	2.2	12.5
Total					
Flash Rate					
Maximum	20.0	1.1	5.0	6.6	31.3
Total					
Flash Rate					
Analysis	2204 -	1935 -	1935 -	1840 -	1629 -
Period	2358	2049	2128	2132	1834
(HHMM,					
UTC)					

Table 1. Summary of NA LMA total lightning properties for the five cells analyzed during DC3 over Northern Alabama.

After both ARMOR and KHTX radar data are gridded to a common Cartesian plane, NCAR's Custom Editing and Display of Reduced Cartesian Space (CEDRIC) tool was used for the multi-Doppler wind synthesis [Miller and Frederick 1998]. A variational integration method of the mass continuity equation was invoked due to the expected minimization of divergence errors at the upper boundary condition when determining vertical motion from estimates of the U and V components of the horizontal wind as well as estimates of Multi-Doppler vertical motions were particle fall speed. estimated for all presented DC3 Alabama cases except During this time period, maintenance being 6/14/2012 performed on KHTX required the use of VCP (Volume Coverage Pattern) 21 and VCP 32. Both of these VCPs severely limit the ability for KHTX to sample convection on an acceptable temporal and spatial scale for multi-Doppler wind synthesis. Accordingly, results from the multi-Doppler wind synthesis on the 6/14/2012 case day are not reported due to the likely error. On all other days, KHTX was in VCP 11, which was suitable for multi-Doppler analysis.

The individual NA LMA VHF radiation sources were clustered into a lightning flash based on spatial and temporal criteria outlined in McCaul et al. [2005]. Furthermore, an additional 10 or more VHF radiation source constraint was applied to the clustered VHF sources in order for it to be classified as a "true" flash in this dataset. This was an attempt to remove erroneous VHF radiation sources (e.g. noise). Wiens et al. [2005] reported that for higher flash rate storms, the selection of a minimum source number criterion can have a large impact on the magnitude of the estimated total lightning flash rate while the trends are conserved. Sensitivity tests using 5, 10, and 15 VHF radiation minimum source number criteria showed very little variation in terms of the number of flashes between each criteria, which is likely due to the low-tomoderate flash rates in DC3 Alabama storms (Table 1) [Bain 2013]. Following Wiens et al. [2005], a ten or more VHF source criterion was deemed appropriate for the DC3 Alabama

NA LMA dataset. In this analysis, there was no upper limit on the amount of VHF radiation sources that can comprise a flash. For total lightning flash rate computations, the first VHF radiation source in each flash was stored and counted over a given radar volume (radar volume time is defined as the time between each successive radar volume). The sum of the total lightning flash counts during the radar volume divided by the radar volume time (in minutes) itself yields the total lightning flash rate (# min⁻¹). A flash extent or length scale was calculated as the square root of the convex hull area surrounding the NA LMA VHF sources in the horizontal for each flash [Bruning and MacGorman 2013].

For all radar and lightning observations, a subjective Lagrangian approach was used to identify and track convective cells (and its associated elements) throughout its lifecycle. Characteristics of the cell or cells of interest (e.g. graupel echo volume/mass, initial VHF radiation source) were restricted to a given analysis box drawn subjectively in an attempt to avoid contamination from neighboring convective cells. While tedious, this subjective approach was deemed more practical and accurate than an automated cell tracking algorithm for this complex mode of multicell convection.

Additional details on the data and methodology used in this study can be found in Bain [2013].

V. RESULTS AND DISCUSSION

A. Overview of Cell B2, 21 May 2012

Using DC3 radar and lightning observations of five multicell thunderstorms over northern Alabama on 5/18/2012 (Cell A1), 5/21/2012 (Cells B1, B2), 6/11/2012 (Cell C1) and 6/14/2012 (Cell D1), several flash rate parameterizations were tested, including those based on radar inferred 1) graupel echo volume; 2) graupel mass, 3) convective updraft volume (> 5 m s⁻¹), 4) maximum updraft and 5) 30 dBZ echo volume. All quantities were calculated within the height layer associated with the -10 °C to -40 °C NIC zone. As noted earlier, retrieved updraft velocities from multi-Doppler synthesis were not available for Cell D1 on 6/14/2012. Note that the term "cell" is used loosely here. The "cells" or storms were actually multicell convective systems with complex yet contiguous reflectivity echo [Bain 2013]. Each "cell" (i.e., multicell complex) was observed for approximately 2 hours (or more) through nearly a full multicell life cycle. Overall, the DC3 Alabama convective cells produced low-to-moderate flash rates (Table 1).

Before presenting the development and testing of radarbased flash rate parameterizations, the evolution of lightning and radar observables for Cell B2 on 5/21/2012 are first overviewed. The summary of Cell B2 demonstrates the physical and statistical correlation between the radar and flash rate trends, providing context for the parameterizations. It also affords an opportunity to explore the relationship between radar and other lightning characteristics such as flash extent and type. Details on the storm structure and evolution of the microphysical and kinematic properties can be found in Bain et al. [2013] for Cell A1 on 5/18/2012 and for all five cells in Bain [2013].



Fig. 2. Evolution of the NA LMA total (IC+CG) and NLDN CG lightning flash counts versus storm kinematic properties in the -10 °C to -40 °C layer for Cell B2 on 5/21/2012. Flash count versus a) maximum updraft velocity (m s⁻¹) and b) updraft volume (m³), including storm volumes exceeding updraft thresholds of 3 m s⁻¹ and 5 m s⁻¹.

The evolution of NA LMA total (IC+CG) and NLDN CG lighting relative to the dual-Doppler derived kinematic properties in the charging region (i.e., in the -10 °C to -40 °C layer) are shown in Fig. 2. The maximum updraft reached 5 -6 m s⁻¹ in the charging region before lightning occurred in Cell B2 (Fig. 2a). As shown in Bain [2013], this surge in the updraft was associated with the lofting of supercooled drops (i.e., formation of a Z_{dr} column), which later froze and likely participated in rapid NIC prior to the onset of lightning. A maximum updraft exceeding 6 m s⁻¹ and the lofting of supercooled raindrops at $T < -10^{\circ}C$ prior to first lightning in warm based clouds is consistent with Zipser and Lutz [1994] and Carey and Rutledge [2000], respectively. The maximum updraft increased rapidly in advance of the total lightning flash rate but peaked shortly after the peak in the total lightning. Overall, the maximum updraft is reasonably correlated ($\rho =$ 0.68) to the NA LMA total flash rate (Fig. 2a).

The updraft volume in Fig. 2b is well correlated to the updraft volume > 3 m s⁻¹ ($\rho = 0.88$) and > 5 m s⁻¹ ($\rho = 0.81$). Although the > 3 m s⁻¹ updraft volume was slightly better correlated to flash rate in this cell and other low flash rate storms such as Cell B1 on 21 May [Bain 2013], the > 5 m s⁻¹ updraft volume was generally better correlated to total flash rate in higher flash rate storms and the overall DC3 Alabama dataset [Bain 2013]. As such, the updraft volume > 5 m s⁻¹ will be used for flash rate parameterizations in the following sections, similar to Deierling and Petersen [2008]. The updraft volume > 5 m s⁻¹ likely identified the portion of the convective cell with sufficient vertical motion to loft large precipitation ice, riming growth, NIC and subsequent lightning production.

The 30 dBZ echo volume in the charging region provided a well correlated ($\rho = 0.82$) envelope around the period of total lightning activity (Fig. 3a). The PID graupel echo volume in the same -10 °C to -40 °C layer matched up to the peaks and

valleys in the total lightning flash rate even better ($\rho = 0.90$) [Fig. 3a], which is consistent with Carey and Rutledge [1996], Wiens et al. [2005] and other studies. Similarly, the graupel mass in the charging region is also well correlated to the total flash rate ($\rho = 0.89$) [Fig. 3b], similar to Carey and Rutledge [2000] and Deierling et al. [2008]. In fact, for all five DC3 Alabama cells, it is interesting to note that the graupel echo volume was similarly correlated to the total flash rate as the This result suggests that the extra step of graupel mass. calculating graupel or precipitation ice mass from a Z-M relationship, which is full of many assumptions [e.g., Carey and Rutledge 2000; Deierling et al. 2008], may be unnecessary. Simply identifying the volume of cloud containing graupel may be sufficient to parameterize the total flash rate. This hypothesis will be tested in the subsequent sections.

The total flash rate in Cell B2 was dominated by IC lightning as the CG flash rate was much lower (Figs. 2 and 3). Furthermore, the NLDN CG flash rate was poorly correlated to the NA LMA total flash rate ($\rho = 0.38$). The lack of correlation between CG and total lightning, even in an ordinary multicell thunderstorm, is important to note as some LNO_x studies have attempted to estimate total lightning from observations of NLDN CG lightning and a regional IC:CG ratio [e.g., Cummings et al. 2014]. Also, note that the NLDN CG flash rate was not particularly well correlated to the maximum updraft ($\rho = 0.51$), the > 5 m s⁻¹ convective updraft volume ($\rho = 0.43$), the graupel echo volume ($\rho = 0.51$) or graupel mass ($\rho = 0.48$) in the -10 °C to -40 °C layer in Cell B2 (Figs. 2 and 3). Carey and Rutledge [1996] hypothesized that the CG flash rate was associated with the descent of the precipitation ice core and hence better correlated to the graupel echo volume at $T > 0^{\circ}$ C. Although outside the scope of the current paper, this hypothesis will be tested with the DC3 Alabama dataset to determine if CG flash rates can be parameterized by radar observables, particularly if flash type is



Fig. 3. Evolution of the NA LMA total (IC+CG) and NLDN CG lightning flash counts versus storm microphysical properties in the -10 °C to -40 °C layer for Cell B2 on 5/21/2012. Flash count versus a) 30 dBZ echo volume (m³) and PID graupel echo volume (m³), and b) PID graupel mass (kg).

determined to be important for LNO_x parameterizations in the WRF-Chem.

The NA LMA flash extent, which was calculated from the square root of the convex hull area surrounding the VHF sources in the horizontal [Bruning and MacGorman 2013], is provided in Fig. 4. In general, the flash extent lagged the flash rate and other measures of convective vigor seen in Figs. 2 and 3. For example, the NA LMA flash extent increased rapidly after Cell B2 became more convectively vigorous as indicated by the peaks in total flash rate (Fig. 2), maximum updraft (Fig. 3a), updraft volume (Fig. 3b) and graupel echo volume/mass (Figs. 4a,b) lining up with the increase in flash extent around 2024 UTC in Fig. 4. After the convective surge weakened and the maximum updraft, updraft volume and graupel volume/mass began to decrease between 2024 and 2035 UTC, the median flash extent continued to increase and then plateaued and the overall distribution of the flash extent greatly broadened (i.e., there were both small and large flashes present after the convective surge). Weaker convective surges in Cell B2 that were characterized by relative maxima in flash rate, updraft and graupel volume/mass at 2045 and 2056 UTC (Figs. 2 and 3) were associated with corresponding temporary decreases in the median flash extent (Fig. 4). In essence, the flash extent and flash rate in this multicell storm were generally opposed as theorized and observed by Bruning and MacGorman [2013] in supercell storms. More specifically, the presence of smaller flashes was associated with peaks in the convective generator while larger flashes were associated with lulls in the convective generator after large swaths of ice aloft had been produced. When a mixture of both conditions were present (i.e., weak convective surges with ample ice aloft), a wide distribution of flash extents were produced.

Based on the finding that convective surges in the charging zone (-10 °C to -40 °C layer) preceded flash extent, the non-

precipitation ice volume aloft, or in and near the top of the convection in Cell B2 ($Z_h > 10$ dBZ and T < -40° C), was calculated and compared to the flash extent (Fig. 4). The non-precipitation ice volume aloft was well correlated with the trend in the median flash extent. Both properties increased between 2004 and 2029 UTC and then plateaued with minor oscillations for the next ~ 35 minutes before both dramatically decreased after 2104 UTC. Decreases in flash extent around 2045 and 2056 UTC were nearby minor decreases in non-precipitation ice volume aloft (i.e., both properties oscillated during this period).



Fig. 4. Evolution of the NA LMA flash extent (km) and non-precipitation ice volume (m³) for Cell B2 on 5/21/2012. The non-precipitation ice volume is calculated for T < -40° C and $Z_h > 10$ dBZ. The grey box represents the interquartile range (IQR) (25–75%) of flash extent while the horizontal line that divides the box into two sections is the median. The upper whisker is the (75th percentile + 1.5xIQR), and the lower whisker is the (25th percentile - 1.5xIQR) [Wilks, 2006]. Any values larger (smaller) than the upper (lower) whisker are seen as outliers and are shown as circles. When there is only 1 flash in the timeframe, it is represented by a black horizontal line.



Fig. 5. A scatterplot of NA LMA total lightning flash rate versus a) updraft volume (m^3) greater than 5 m s⁻¹ within the -10 °C and -40 °C layer for all DC3 AL cases excluding 14 June 2012 and b) maximum updraft velocity (m s⁻¹) within the -10 °C and -40 °C layer for all DC3 AL cases excluding 6/14/2012. In each panel, the filled circles are color coded by date. Blue circles correspond to data points of complex A1 (5/18/2012), red circles correspond to complex B1 and B2 (5/21/2012), and orange circles correspond to complex C1 (6/11/2012). The red line represents the best fit line to all of the data points.



Fig. 6. Scatterplot of NA LMA total lightning flash rate versus a) graupel echo volume (m^3) and b) graupel mass (kg) within the -10 °C and -40 °C layer for all DC3 AL cases. In each panel, the filled circles are color coded by date. Blue circles correspond to data points of complex A1 (5/18/2012), red circles correspond to complex B1 and B2 (5/21/2012), orange circles correspond to complex C1 (6/11/2012) and black circles correspond to complex D1 (6/14/2012). The red line represents the best fit line to all of the data points.

More research is required to better understand the relationship between flash extent and the kinematic and microphysical properties of convection. If progress is made on this subject, it is likely to lead to improvements in LNO_x parameterizations in models, which currently assume that every flash is the same (i.e., do not consider flash extent). For now, we turn our attention to the parameterization of total flash rate from radar observed kinematic and microphysical properties, since current LNO_x parameterizations rely on flash rate from similar model parameters [Barthe et al. 2010; Cummings et al. 2014].

B. Development of Total Flash Rate Parameterizations

The NA LMA total lightning flash rate versus the updraft volume $> 5 \text{ m s}^{-1}$ (Fig. 5a) and the maximum updraft speed (Fig. 5b) in the charging region are shown for the four cells with available multi-Doppler retrieved vertical velocities along with best fit lines. The associated equations and other details

regarding the best fit lines can be found in Table 2. The lines are reasonable fits to the total flash rate versus updraft volume (Fig. 5a) and maximum updraft (Fig. 5b) data but there are outliers from Cell A1 (5/18/2012) that bias the lines upward in flash rate for a given updraft quantity. The flash rates from Cell A1 behaved somewhat non-linearly relative to updraft properties and were fairly distinct from Cells B1 and B2 (5/21/2012) and C1 (6/11/2012). Cell A1 had significantly larger mean and maximum flash rates than Cells B1, B2 and C1 (Table 1). Unfortunately, no vertical motion data were available from Cell D1 (6/14/2012), which also had larger mean and maximum flash rates; so it is not possible to verify this apparent bifurcation in total lightning versus updraft behavior between low (Cells B1, B2, and C1) and high flash rate storms (Cell A1). As shown in the next section, the outliers and scatter from the best line (Table 2) affected the performance of the updraft based total flash parameterizations in this DC3 Alabama dataset.

Table 2. Equations to estimate total flash rate (Y) from DC3 Alabama radar observables (X) using a best fit line, which are shown in Figs 5 - 7. The linear model was fit to the data in Figs. 5-7 by minimizing the chi-square error statistic and setting the y-intercept to zero (i.e., Y=0, X=0).

Radar Observable (X)	Sample Size (# of points)	Pearson Correlation Coefficient	Best Fit Line to Predict Total	Root Mean Square Error	Mean Square
		(p)	Flash Rate (Y) from X		Error
Graupel Echo Volume	200	0.91	$Y = 5.6 \times 10^{-11} \cdot X$	2.7	7.29
Graupel Mass	200	0.90	$Y = 2.43 \times 10^{-8} \cdot X$	3.05	9.3
30 dBZ Echo Volume	200	0.83	$Y = 1.73 \times 10^{-11} \cdot X$	4.14	17.1
Updraft Volume $> 5 \text{ m s}^{-1}$	136	0.65	$Y = 1.72 \times 10^{-11} \cdot X$	2.8	8.13
Maximum Updraft Velocity	136	0.59	$Y = 0.42 \cdot X$	3.3	11

The NA LMA total lightning flash rate versus the graupel echo volume and graupel mass in the charging region are provided in Figs. 6a and 6b, respectively, along with a best fit line for all five storms. Although there is some evident scatter off of both lines, there is steadily increasing total lightning flash rate for increasing graupel echo volume and mass (Fig. 6) across all five cases as expected from prior research [Carev and Rutledge 1996; Carey and Rutledge 2000; Wiens et al. 2005; Deierling et al. 2008]. As a result, there are no cells or storm days for which the expected total lightning for a given graupel quantity is significantly more biased off of the best lines than the others. As such, graupel echo volume or mass appear to be more robust indicators of total lightning flash rate for this limited data set during DC3 over northern Alabama (Table 2). This preliminary finding will be tested and made more quantitative in the next section.

The NA LMA total lightning flash rate versus the 30 dBZ echo volume in the charging region for all five cases along with a best fit line is shown in Fig. 7. The high flash rate storms (Cell A1 on 5/18/2012 and D1 on 6/14/2012) exhibited noticeably different behavior than the low flash rate storms (Cells B1 and B2 on 5/21/2012 and Cell C1 on 6/11/2012). The total flash rate was somewhat non-linear relative to the 30 dBZ echo volume for the high flash rate storms as the flash rate sincreased above 10 flashes min⁻¹. The data from the low flash rate cells exhibited much more obviously linear behavior. As a result, there appeared to be a cell specific bias of the total flash rate versus 30 dBZ echo volume data relative to the best fit line. For sure, there was significant scatter off of the best fit line, including at low flash rates (Table 2). Both of these preliminary findings will be evaluated in the next section.

C. Testing of Total Flash Rate Parameterizations

The total flash rate versus radar observable linear equations in Table 2, which were derived from the data in Figs. 5 - 7, were used to estimate total flash rates from the actual cellbased radar observables for each cell at each time and were compared to the magnitude and trend of the actual observed NA LMA total flash rates (i.e., "truth") (Fig. 8). Qualitatively, all the radar estimated flash rates agreed reasonably well with the observed total flash rate. Although there were some differences in the performance of radar based flash rate estimators between one cell and another, qualitative inspection of Fig. 8 leads one to conclude that the total flash rates estimated from the graupel volume appeared to do the best in terms of flash rate magnitudes and trends when considering all cells together, closely followed by the flash rate estimated from graupel mass.



Fig. 7. Same as Fig. 6a except for 30 dBZ echo volume (m³).

These qualitative impressions were made more quantitative with various performance metrics. A histogram of the per cell correlation coefficients between radar estimated and NA LMA observed total flash rates (Fig. 8) are provided in Fig. 9. Similarly, histograms of the per cell standard errors and bias errors for the radar estimated flash rates relative to NA LMA "true" flash rates are provided in Figs. 10 and 11, respectively. Performance metrics averaged over all available cells are provided in Table 3. Again, although there are some exceptions for individual cells, total flash rates estimated from the graupel echo volume had the consistently highest correlations (Fig. 9), lowest standard error and normalized standard error (Figs. 10a,b) and lowest bias error and normalized bias error (Figs. 11a,b). As noted earlier, flash rates from the graupel mass performed nearly as well. Flash rates inferred from graupel mass were a close runner-up to and in some cells indistinguishable from flash rates estimated from graupel echo volume. Flash rates estimated from 30 dBZ echo volume, updraft volume and maximum updraft had significantly higher standard error than flash rates estimated from graupel echo volume and graupel mass. Flash rates inferred from 30 dBZ echo volume and maximum updraft velocity had significantly higher bias errors than flash rates estimated from graupel echo volume, graupel mass and updraft volume. Table 3 summarizes these quantitative conclusions.



VI. SUMMARY

In summary, analysis of five long lived multicell convective complexes observed during DC3 over northern Alabama demonstrated that radar kinematic (maximum updraft, convective updraft volume) and microphysical (graupel echo volume, graupel mass, 30 dBZ echo volume) observables in the charging zone (-10 °C to -40 °C layer) are qualitatively correlated to the NA LMA observed total flash rate. Specific linear equations were developed and tested from this DC3 Alabama data set to estimate total flash rate from these radar observables. Among the radar observables tested, graupel echo volume provided the most robust and accurate estimate of total flash rate for all DC3 Alabama cells, closely followed by the graupel mass. Based on this limited data set, it appears that a total flash rate can be reasonably estimated by simply knowing the volume of cloud containing graupel in the



Fig. 8. Evolution of the NA LMA total lightning flash rate (TLFR) (black line) and radar estimated TLFR (color coded lines as shown) for a) Cell A1 (5/18/2012), b) Cell B1 (5/21/2012), c) Cell B2 (5/21/2012), d) Cell C1 (6/11/2012) and e) Cell D1 (6/14/2012). The radar retrieved flash rates were estimated from the best fit lines shown in Figs. 5 – 7 using the actual radar data associated with each cell at each time. Note that multi-Doppler retrieved vertical motions were not available for e) Cell D1 on 6/14/2012.

charging zone. In other words, the assumption filled and often error prone step of estimating graupel ice mass from reflectivity (Z-M) appears to be unnecessary. Based on published CRM simulations, it is likely that this conclusion will hold for models as well. For example, Kuhlman et al. [2006] found a strong correlation between model derived flash rates and model estimated graupel echo volumes.



Fig. 9. Correlation coefficient (ρ) between the actual NA LMA observed total flash rate and each radar derived total flash rate for each cell shown in Fig. 8.



Fig. 10. The a) standard error (flash min⁻¹) and b) normalized standard error for each radar estimated total flash rate (color coded) relative to the actual NA LMA observed total flash rate for each cell shown in Fig. 8. The normalized standard error is the standard error normalized by the average NA LMA flash rate for each cell (Table 1).



Fig. 11. The a) bias error (flash min⁻¹) and b) normalized bias error for each radar estimated total flash rate (color coded) relative to the actual NA LMA observed total flash rate for each cell shown in Fig. 8. The normalized bias error is the bias error normalized by the average NA LMA flash rate for each cell (Table 1).

There were some significant bias and standard (i.e., scatter) errors associated with flash rates inferred from the other radar observables. Part of the problem appears to be bifurcation in the behavior of total flash rate versus these radar observables in lower versus higher flash rate storms. Given that the DC3 Alabama cells were characterized by low-to-moderate flash rates, these errors might continue to grow if storms from other regions are included into this analysis. Future work with the DC3 Alabama dataset will include the exploration of nonlinear fits to the total flash rate versus radar observable data set to see if the performance of some of the flash rate parameterization schemes improves. In future work, these results will also be compared and evaluated against the relationships found in the published literature [e.g., Barthe et al. 2010] and from other DC3 regions [Basarab et al. 2013]. Based on preliminary analysis, it is possible that specific results and conclusions might vary regionally.

Finally, flash extents were related to rates and radar observables in a single multicell storm during DC3 Alabama. The flash extents and rates were generally opposed as theorized and observed by Bruning and MacGorman [2013] in supercell storms. More specifically, the presence of smaller flashes was associated with peaks in the convective generator (e.g., peaks in flash rate, graupel volume, updraft volume, maximum updraft) while larger flashes seemed to be associated with lulls in the convective generator after large swaths of ice aloft had been produced. When a mixture of both conditions were present (i.e., weak convective surges with ample ice aloft), a wide distribution of flash extents were produced. The nonprecipitation ice volume aloft was well correlated with the trend in the median flash extent. Future work will explore these relationships in a variety of storm types.

all available cells.							
Radar Observable	Average Correlation Coefficient (ρ)	Average Normalized Standard Error (NSE)	Average Absolute Normalized Bias Error (NBE)				
Graupel Echo Volume	0.81	0.70	0.25				
Graupel Mass	0.80	0.71	0.33				
30 dBZ Echo Volume	0.79	1.24	1.56				
Updraft Volume > 5 m s ⁻¹	0.74	1.10	0.39				
Maximum Updraft Velocity	0.66	1.51	2.21				

Table 3. Average cell-based performance of the radar estimated total flash rate relative to the actual NA LMA (i.e., "true") total flash rate for all DC3 Alabama cells shown in Fig. 8. The performance metrics were averaged for all available cells.

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