Using Radar-Derived Parameters to Forecast Lightning Cessation for Nonisolated Storms

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USING RADAR-DERIVED PARAMETERS TO FORECAST LIGHTNING CESSATION FOR NONISOLATED STORMS

By

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ABSTRACT

Lightning inhibits normal operating conditions at the Kennedy Space Center (KSC) and other locations, leading to inconvenience and detrimental economic impacts. Lightning cessation guidance must safely protect lives and infrastructure. This research focuses on “nonisolated” lightning cases which we defined as one cell whose flashes had ceased while embedded in weak composite reflectivity ($Z \geq 15$ dBZ) with another cell still producing flashes. The dataset consisted of 50 warm season (May-September) nonisolated storms near KSC during 2013. The research utilized the National Lightning Detection Network (NLDN), the second generation Lightning Detection and Ranging (LDAR-II), and polarized radar data. These data were merged and analyzed using the Warning Decision Support System-Integrated Information (WDSS-II) at 1 min intervals. The parameters, such as horizontal reflectivity ($Z_H$), that decreased greatest during the cessation period were $Z_H > 40$ dBZ at -5°C, $Z_H > 35$ dBZ at -10°C, graupel presence at -10°C, and graupel presence at -15°C. We tested 60 cessation schemes utilizing a wait time approach. Our safest scheme required that the distance from our decaying storm’s 30 dBZ core to the closest signature of graupel associated with the active storm (30G) be greater than 10 nm (~19 km) and horizontal reflectivity be less than 40 dBZ at -5°C for 10 min. In the independent (dependent dataset), this scheme produced one (zero) false alarm. More research is needed to analyze nonisolated cessation, since no algorithm produced perfect skill when applied to the independent dataset.
CHAPTER ONE
INTRODUCTION

1.1 Motivation

Lightning is a deadly weather phenomenon killing 261 people between 2006-2013 in the United States alone (Jensenius 2014). During Florida’s warm season, lightning is a daily threat due to thunderstorms associated with the local sea breeze circulation. The Florida peninsula exhibits the greatest flash density in the continental United States (Orville and Silver 1997; Huffines and Orville 1999; Rudlosky and Fuelberg 2011; Orville et al. 2011; Makela et al. 2011). The U.S. Air Force 45th Weather Squadron (45WS) at the Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) produces real time advisories of lightning initiation and cessation to protect lives and infrastructure in the KSC/CCAFS area. These advisories increase personnel safety by utilizing advanced sensors including field mill data, a lightning mapping array, polarized radar, and a mesoscale surface network.

Lightning strikes also damage property. For example, during its launch in 1987, Atlas/Centaur 67 was struck by lightning that destroyed the rocket and its instruments costing $190 million (Christian et al. 1989; Orville 2008). This catastrophe led to the creation of the Lightning Launch Commit Criteria (LLCC) which provides a detailed protocol that must be met for a launch to proceed (McNamara et al. 2009). In addition to impacts on rocket launches, improved lightning cessation guidance will provide a positive economic impact. Work delays in the KSC/CCAFS area due to lightning safety protocols lead to financial loss. Roeder et al. (2014) stressed that research into lightning cessation is KSC’s number one priority. Ending lightning advisories efficiently would provide savings in both time and money for KSC.

A better understanding of lightning cessation will aid numerous other sectors, including airport ground operations and outdoor sporting events. Many outdoor interests use the well-known 30/30 rule for lightning safety (e.g., Holle et al. 1999) whose second component includes waiting at least 30 min after no lightning has occurred before resuming outdoor activities. The present study seeks to safely shorten the wait time of previous guidelines, such as the 30/30 rule or the wait time presently used by the 45WS.

1.2 Background on Thunderstorm Electrification

Several mechanisms for the electrification of thunderstorms have been proposed, with the
non-inductive charge (NIC) mechanism being most prominent. Electrical charge is transferred when collisions occur between graupel and smaller ice crystals in the presence of supercooled water in the storm’s mixed phase layer (0°C to -20°C) (e.g. Takahashi et al. 1973; Jayaratne et al. 1983; Saunders et al. 1991). Following these collisions, the lighter, positively charged ice crystals are lofted by the storm’s updraft, while the heavier, negatively charged graupel particles remain within the -10°C to -20°C region. Although the vertical electrical structure of thunderstorms varies (Rust and Marshall 1996), a tripole charge structure is often observed with a shallow positive layer near 0°C, a strong negative layer between -10°C to -20°C, and a positive layer above -20°C (Krehbiel 1986; Williams 2001). Lightning occurs when the electrification of these layers reaches a discharge threshold, either in the form of in-cloud (IC) or cloud-to-ground (CG) flashes of positive or negative polarity.

The microphysical properties of thunderstorm anvils and mesoscale convective systems (MCSs) increase the complexity of forecasting lightning cessation. Both idealized single cell storms and larger MCSs produce lightning that affects central Florida. Lang and Rutledge (2008) investigated the kinematic, microphysical, and electrical aspects of an MCS over Colorado during the Severe Thunderstorm Electrification and Precipitation Study. They observed varying vertical charge structures between an asymmetrical bow echo and its trailing stratiform region. Lightning activity in the anvil of thunderstorms is an especially complex and poorly understood phenomenon. The anvils of thunderstorms exhibit large spatial and temporal gradients of electrical field (Dye et al. 2007). Kuhlman et al. (2009) found cases of anvil-initiated lightning that were hypothesized to be caused by the convergence or confluence of charge, as well as local charging within the anvil itself. IC lightning has been observed between the anvils of two supercells in areas of minimal (< 20 dBZ) radar reflectivity (Z) (Weiss et al. 2009). Although not the focus of the present study, we observed anvil initiated CG flashes traversing regions of minimal reflectivity. Stolzenburg et al. (2010) found strong values of electric field (E) in anvils long after the final lightning flash had occurred.

1.3 Previous Research on Lightning Cessation

The first and last flashes of a storm are the most dangerous (Holle et al. 1992). Thus, previous studies have examined both lightning initiation (e.g., Marshall et al. 1995, 2005; Gremillion and Orville 1999; Wolf 2006) and cessation (e.g., Stano et al. 2010; Anderson 2010;
Carey et al. 2009; Shultz et al. 2013; Seroka et al. 2012; Preston and Fuelberg 2015). Values of horizontal reflectivity ($Z_{H}$) at various thermal levels have been used to develop guidance algorithms for initiation and cessation. Wolf (2006) found a probabilistic relationship between 40 dBZ horizontal reflectivity at the -10°C level and CG flashes. However, this relationship did not provide sufficient guidance for lightning cessation since Anderson (2010) observed several cases in which cessation occurred when $Z_{H}$ exceeded 40 dBZ at the -10°C level. The percentile method (percentiles of the maximum time interval between flashes) (Stano et al. 2010) was found to be the only statistical/empirical scheme to show promise in safely ending advisories, with ~25 min being the optimal flash interval to wait before ending an advisory. This produced a time savings of 5-10 min compared to the 30/30 rule (Holle et al. 1999). Preston and Fuelberg (2015) incorporated polarized radar data to derive a cessation algorithm for isolated cells which they defined as storms that were not linked to nearby electrically active storms by composite reflectivity >15 dBZ. Using a hydrometeor classification algorithm (HCA) to identify the presence of graupel, they found that cessation for their independent dataset’s isolated cells could be assumed 10 min after graupel and $Z_{H} > 35$ dBZ at -10°C were no longer present. However, this algorithm failed to safely end advisories for nonisolated storms. The present study extends the work of Preston and Fuelberg (2015) (hereafter PF15) by examining nonisolated storms with the intent of increasing our knowledge of cessation guidance for them.

The continued electrification of decaying thunderstorms is a crucial topic for understanding lightning cessation. Marshall and Lin (1992) lofted balloons that measured electric fields (E) in decaying thunderstorms. The soundings revealed values of E that were 3-4 orders of magnitude greater than typical discharged clouds. A vertical shifting of charge layers from the late mature stage has been observed during the End of Storm Oscillation (EOSO; Fig. 1) (Marshall et al. 2009). In a nonisolated situation, nearby storms can be at different stages of their lifetime. We hypothesize that this could lead to an increased likelihood of electrical interaction (leading to a flash) between nonisolated storms, due to varying horizontal charge gradients. Stolzenburg et al. (2010) observed E values in anvilsthat were great enough to endanger aircraft as long as 50 min after a storm’s last flash. The positively charged anvil of a thunderstorm retained sizeable E values after the lifetime of, and away, from the parent convection. Zhang (2014) found that precipitation associated with a storm’s downdraft depleted the lower positive layer of a storm’s tripole charge structure. They also observed a strong
electric field over 2 h after the final flash in a nonisolated environment. The charge density of the storm actually increased from the first balloon sounding (20 min after the last flash) to the second sounding (138 minutes after last flash). Zhang hypothesized that this increase was due to lowering of cloud top height that subsequently compressed the charge. Another possibility is that the storm was still weakly charging, but no flash consumed that charge. These characteristics make forecasting lightning cessation for nonisolated scenarios a difficult task since remnant charge can aid in initiating a flash that traverses a decaying storm

![Figure 1](image-url)  
Figure 1. The progression (left to right) of charge layers from the mature stage through the EOSO for a storm observed in New Mexico. Gray (red) boxes indicate positively (negatively) charged layers. The width of the boxes represents the magnitude of the positive (negative) charge layer. The outline of the area represents the cloud extent from 3.5 to 9.5 km vertically, and 12 km horizontally (After Marshall et al. 2009).

### 1.4 Objectives

PF15 tested their cessation algorithm for isolated storms on a set of nonisolated cases and found that it provided unacceptable results. Therefore, the major objective of our study is to increase the understanding of nonisolated storms to aid in creating lightning cessation guidance for them near KSC/CCAFS. PF15 defined nonisolated cases as decaying storms that experienced cessation while still connected with other nearby actively charging storms by composite reflectivity greater or equal 15 dBZ. We used a larger dataset of nonisolated cases (50) than PF15 (30) to provide more robust results. Storm characteristics as the decaying storm neared cessation were monitored and analyzed. Numerous cessation schemes based on previous research were tested. Results from the dependent dataset were tested on the independent dataset. Finally, case studies were performed on “outlier” storms whose lightning behavior differed from the norm.
We address the following questions regarding the lightning cessation of nonisolated storms:

a. Can any limiting factors be used to accurately represent lightning cessation in a nonisolated scenario?

b. Which cessation schemes (including PF15’s isolated scheme) perform well in our larger dataset of nonisolated storms?

c. For nonisolated cases whose trends in graupel and reflectivity during cessation are atypical, what causes these storms to be different?
CHAPTER TWO  
DATA AND METHODOLOGY

2.1 Data

Lightning source data were obtained from the KSC Lightning Detection and Ranging second-generation (LDAR-II) network (Lennon 1975; Poehler and Lennon 1979; Maier et al. 1995; Britt et al. 1998; Boccippio et al. 2001; Roeder 2010). LDAR-II is a lightning detection network that senses in three-dimensional space the individual sources of radiation emitted by lightning in the very high frequency (VHF) range near 66 MHz (Boccippio et al. 2001). LDAR-II has a flash (source cluster) detection efficiency exceeding 90% (Roeder 2010) within our study’s domain of radius 100 km from the center of the network (same as PF15). Data from the National Lightning Detection Network (NLDN; Orville 2008) also were used because LDAR-II seldom detects CG strike locations. Using time of arrival and direction-finding techniques, the NLDN triangulates a location from the very low frequency/low frequency (VLF/LF) emitted radiation with 90% stroke detection efficiency and a typical location error of 250 m (Cummins and Murphy 2009).

National Weather Service WSR-88D radar data from Tampa, FL and Melbourne, FL (KTBW and KMLB) were obtained from the National Climatic Data Center (NCDC). The hydrometeor classification algorithm (HCA) within the radar software (Scharfenberg et al. 2007; Park et al. 2009) was used to identify areas of graupel which are important to noninductive charging. The HCA algorithm uses a fuzzy logic scheme to assign particle identification values. It is important to note that the HCA only indicates the predominant hydrometeor type within each radar volume (Woodward et al. 2012). Thus, if the HCA indicates a type other than graupel in the mixed phase layer, some graupel may still be present. The heights of thermal levels (e.g., -10°C) were obtained from the Rapid Refresh (RAP) model (Benjamin and Sahm 2015), an upgrade of the Rapid Update Cycle that now implements both the Weather Research and Forecast model and Gridpoint Statistical Interpolation analysis from the National Centers for Environmental Prediction (NCEP). The analysis data of the RAP model has 13 km horizontal grid spacing and 50 vertical levels, ending at 10 hPa.

Lightning, radar, and temperature data were analyzed three dimensionally using the Warning Decision Support System-Integrated Information (WDSS-II, Lakshmanan et al. 2007b) software. The tool w2qcnndp was used to quality control the polarized data, identifying and
eliminating clear air returns, ground clutter, and anomalous propagation (Lakshmanan et al. 2014). The WDSS-II tool w2merger combines data from multiple radars (e.g., Melbourne and Tampa) into a rapidly updated (~1 min) 3D grid of radar data (Lakshmanan et al. 2006). Values are merged using a distance weighted exponential function. This merged product decreases the limitations of temporal resolution and vertical coverage that arise from the scanning strategies of single radars. An automated storm tracking tool, w2segmotionl1, employs a K-means clustering technique (Lakshmanan et al. 2009; Lakshmanan and Smith 2009). Storms were tracked using dilated composite horizontal reflectivity. WDSS-II also was used to combine the LDAR-II source data into flashes. Following the methods of PF15, the WDSS-II flash integration algorithm required at least 3 VHF sources within 5 km and 300 ms of one another to be considered a flash. These flashes were binned into 1 min intervals, matching the temporal resolution of our merged products. WDSS-II and its component algorithms were used to analyze the characteristics of flashes in the selected storms.

2.2 Methodology

Our dataset consisted of 50 warm season (May-September) nonisolated storms near KSC/CCAFS during 2013. Great care was taken in defining and selecting cases to ensure a consistent dataset for examining nonisolated cessation. It is important to note that our definition of nonisolated storms was more specific than that used by PF15. Fuelberg et al. (2014) documented IC flashes within anvils over Florida that extended greater than 50 km outside of the 30 dBZ core. We observed a flash that extended 80 km from the 30 dBZ composite core. These and other “lightning extensions” (defined as flashes from an active storm extending into areas of that same storm’s weak composite reflectivity) are not the focus of this study. Our definition of nonisolated cases required one cell whose flashes had ceased and one (or more) cells still producing flashes. The cells’ composite reflectivity cores must be spatially connected by composite reflectivity $\geq 15$ dBZ, similar to PF15. This required connection distinguishes our definition of nonisolated from other possible definitions.

Several additional requirements that were not used in PF15 were added to prevent the inclusion of lightning extensions. The distinction between lightning extensions and our definition of nonisolated cases is shown in Fig. 2a,b. Both cells must have had graupel at -10°C and previous lightning activity initiated inside of their 30 dBZ reflectivity cores. Our definition
also required that the composite reflectivity core of the decaying cell must be greater than 30 dBZ in order to be tracked. These requirements prevented the inclusion of lightning extensions in our dataset.

Figure 2. Idealized differences between a) nonisolated cessation and b) lightning extension. Green represents composite reflectivity between 15 - 30 dBZ, with yellow and red at arbitrary greater values. White lines represent a lightning flash. c) Actual case of nonisolated interaction and d) lightning extension. Merged KTBW and KMLB composite reflectivity is shown with lightning flashes derived from LDAR-II data marked with white lines. Blue (white) circles indicate active (decaying) cells.

The final IC or CG flash that occurs within (but not necessarily initiated within) the 30 dBZ core of the decaying storm is considered its last flash, with its occurrence representing the time of cessation. Once the storm decayed completely (i.e., lost its 30 dBZ composite reflectivity core), the storm’s characteristics were no longer considered. The cell that undergoes
cessation in our cases is considered “decaying.” All other cells that continue to produce lightning are denoted “active.”

Numerous parameters were investigated for their ability to indicate lightning cessation in nonisolated storms. PF15 described a relationship between cessation in isolated storms, $Z_{H} < 35$ dBZ at -10°C, and graupel absence at -10°C. Lightning flash rates also have been related to radar-derived graupel volume, graupel mass, 30 dBZ echo volume, updraft volume, and maximum updraft velocity (Carey et al. 2014). Bruning et al. (2007) found that updraft speed and local maxima of graupel are well correlated with lightning activity in both space and time. The characteristics of flash producing storms versus non-flash producing storms were examined by Palucki et al. (2011). They found that the two differentiating factors were volume of the updraft and polarized signatures associated with graupel in the mixed phase region (0°C to -20°C). Similarly, Matthee et al. (2014) observed stronger updrafts, deeper cloud formations, and considerably more ice in the mixed phase region of convective rainfall associated with lightning compared to non-lightning convective rainfall. We could not investigate the utility of parameters involving vertical velocity due to the absence of Dual-Doppler data in the KSC area. Thus, we focus on reflectivity and the presence of graupel at several different thermal levels.

Additional parameters were examined to determine the characteristics of nonisolated cessation. Nelson (2002) found that 95% of the flashes studied had originated within 3 km of a composite reflectivity core (defined in their study as 40 dBZ) and only 5% of the flashes extended 20-30 km from their origin point. Similarly, Fuelberg et al. (2014) observed IC lightning that extended as far as 50 km from the thunderstorm’s composite reflectivity core (defined as 30 dBZ). These observations suggest that lightning could be channeled from an active cell through a relatively weak area of reflectivity to produce a CG or IC flash near a presumed decaying cell. Thus, the maximum connecting composite $Z_{H}$ between storms, distance between storms, and distance from the decaying storm to the closest region of graupel are potential factors that could limit or enhance the occurrence of flashes. We included each of these parameters in the present study. Finally, Stano et al. (2010) examined the time interval between flashes in an attempt to predict cessation. He determined that 75% of storms had a maximum flash interval less than 7.5 min. Flash interval was included in this study, utilizing a 5 min wait time.
Based on the considerations described above, the following parameters were selected for tracking storms, either manually (M) or using a WDSS algorithm (W):

b. Maximum reflectivity of the decaying storm at 0°C, -5°C, -10°C, -15°C, and -20°C (W).
c. Maximum connecting composite reflectivity between the decaying cell and the active cell. A WDSS-II algorithm was used to create reflectivity contour levels (6 levels between 15-30 dBZ at 2.5 dBZ intervals), with the level recorded manually (W) (M).
d. Shortest horizontal distance between the 30 dBZ composite reflectivity core of the decaying cell and the 30 dBZ composite reflectivity core of the active cell (M).
e. Shortest horizontal distance between the 30 dBZ composite reflectivity core of the decaying cell and a signature of graupel at -10°C associated with the active cell (M).
f. Flash interval of the decaying storm (i.e., minutes since the previous flash) (M).

The aforementioned parameters (14 in all) were recorded at 1 min intervals during the 15 min period prior to and after the lightning cessation of the decaying storm (30 min total). Various thresholds of each parameter were examined, as were combinations of different parameters. This provided a total of 60 different cessation schemes. Statistics showing the temporal variability of these potential parameters with respect to cessation were calculated, including false alarm ratio, probability of detection, success ratio, and critical success index. Each potential algorithm was tested on the 12 independent cases, and the best performing algorithms were identified. Cases where no cessation algorithm was successful were investigated in detail, including the use of KSC’s Advanced Ground Based Field Mill data.

Data collected when the 30 dBZ core did not exist were not analyzed. If more than one active storm was embedded along with the decaying storm, either the closer or more strongly connected via composite reflectivity storm was used, depending on which parameter was being recorded. From the total of 50 nonisolated cases meeting our definition, potential cessation algorithms were first tested on 38 cases, i.e., the dependent dataset. The 12 remaining cases were used later as an independent dataset.
2.3 Uncertainties

The data and methodology are subject the uncertainties that could influence the cessation schemes. Although the polarized data were quality controlled in WDSS-II (Lakshmanan et al. 2013), and the HCA has improved over the years (Scharfenberg et al. 2007; Park et al. 2009), the HCA algorithm does not perfectly represent the presence of graupel. It only indicates the predominant hydrometeor class in the specific radar volume. Though graupel may not be the predominant hydrometeor, it still may be present and cause noninductive charging to occur.

An additional uncertainty involves data collection using the w2segmotion tool within WDSS-II. The algorithm assigns pixels to clusters (storms) based on their intensity relative to the mean intensity of the cluster. A minimum size of the cluster is also specified. This method occasionally would stop tracking a storm’s cluster. Thus, the automated storm tracking fails. Since the tracking of each storm was monitored, we could “take over”, manually, recording the graupel and reflectivity data. This introduces potential human error.

The distance parameters described above were measured manually (in nm) using the WDSS-II vertical slice tool. We estimate the human error using this tool to be ± 1 nm (~1.9 km). Finally, our cessation schemes were analyzed within a 100 km radius of KSC/CCAFS. Thus, the results and conclusions may not be applicable to different locations. In spite of these uncertainties, we believe our results will be useful for advancing the forecasting of lightning cessation.
CHAPTER THREE
RESULTS

3.1 Distributions of the Dependent Dataset

The size of our dependent dataset varied with time during the cessation period (Fig. 3) because we required that the decaying storm must retain its 30 dBZ composite reflectivity value in order to continue being tracked. However, some cases lost their 30 dBZ core shortly after cessation. Since they no longer could be tracked, their characteristics at these times were not included in the analysis. Some cases also were isolated early in their life cycles but later met our definition of a nonisolated cessation case since they became nonisolated well prior (> 10 min) to cessation. Their characteristics were not tracked until their 30 dBZ composite reflectivity cores split, creating a nonisolated cessation scenario. The maximum number of 38 storms (Fig. 3) occurred 10 min prior to cessation and lasted until 1 min after cessation. The minimum (19) occurred 15 min after cessation. This decrease in statistical robustness after cessation should be considered when drawing conclusions from our analysis.

Figure 3. Dataset size distribution vs time (min) relative to cessation for the dependent dataset of 38 cases.

No conclusions should be deduced about nonisolated lightning cessation when examining results from our dependent dataset alone. Results from the dependent data later will be compared to those of the independent dataset using identical methods when making conclusions. We next examine the temporal distributions of radar-derived parameters, describing the nonisolated storms during the 30 min period between 15 min prior to and 15 min after cessation.
Box and whisker plots (Fig. 4a-e) show the distributions of maximum reflectivity for decaying storms at the -0°C (R0), -5°C (R5), -10°C (R10), -15°C (R15), and -20°C (R20) thermal levels. The superimposed reference line at 35 dBZ is based on the results of PF15 who found 35 dBZ at -10°C to best indicate cessation for isolated storms. The median maximum reflectivity value at cessation is ~35 dBZ for R10 and R15. R5 is slightly different, with a median value of 40 dBZ at -5°C. The temporal distributions of R10 and R5 decrease sharply during cessation. For example, at these two thermal levels, the 25\textsuperscript{th} percentile value approximately becomes the 75\textsuperscript{th} percentile value between 5 min before to 5 min after cessation. These strong temporal changes indicate that R5 and R10 may be the optimum reflectivity-based cessation parameters. However, similar to the nonisolated cases in PF15, our dataset has several ‘outliers’ 15 min after cessation. Therefore, using a cessation algorithm consisting only of reflectivity parameters may lead to the unsafe termination of advisories in some cases.

The distributions of three parameters not considered by PF15, but possibly important for nonisolated cessation cases, are displayed in Fig. 4 (f-h). The temporal distributions of maximum connecting composite reflectivity (MCCR) values between the decaying and active storm are considered first. Recall that we defined six reflectivity levels ranging from 15-30 dBZ at 2.5 dBZ intervals. Although a slight decrease in the median values of MCCR is observed during the cessation period, the overall distributions change little (Fig. 4f).

The temporal distributions of distance from the decaying storm’s 30 dBZ contour to the active storm’s 30 dBZ contour (30D) are shown in Fig. 4g. Similarly, the distributions of the distance from the decaying storm’s 30 dBZ contour to the closest signature of graupel in the active storm (30G) are shown in Fig. 4h. The 30D median distance is shorter than the 30G median during the cessation period because the closest graupel signature usually resided inside of the active storm’s 30 dBZ core. Distributions of the two distance parameters vary similarly, with the median distance values remaining almost constant during the cessation period. Although the 75\textsuperscript{th} percentile values for both 30D and 30G decrease, this may be related to the decrease in the size of the dataset (Fig. 3). Due to the relative lack of change in the three new parameters during cessation, a successful cessation algorithm that employs them will require a combination with other parameters.

The temporal variations of graupel presence at the 0°C (G0), -5°C (G5), -10°C (G10), -15°C (G15), and -20°C (G20) thermal levels for the decaying storms are shown in Fig. 5 (a-e,
Figure 4. Box and whisker plots for a) R0, b) R5, c) R10, d) R15, e) R20 (all dBZ), f) MCCR (unitless), g) 30D (nm), and h) 30G (nm) at 5 min intervals before and after cessation. Red lines indicate median values. Blue boxes represent the 25th and 75th percentiles (1st and 3rd quartiles). Whiskers extend to the maximum (minimum) 99.3 (0.7) percentile, with outliers marked as red crosses. A gray reference line at 35 dBZ is overlaid in (a-e).
Figure 5. Scatter plots for a) G0, b) G5, c) G10, d) G15, and e) G20 at 1 min intervals before and after cessation. Values along the y-axis represent the arbitrary case number. Graupel presence (absence) is indicated by red (blue) markers. The plots allow one to observe the presence of graupel for individual cases during the cessation period.

respectively). Red markers indicate the presence of graupel, and blue markers indicate its absence. It is prudent to reiterate that “graupel absence” implies that the HCA algorithm did not indicate graupel as the predominant hydrometeor class. Both G0 and G5 exhibit graupel presence well after cessation. G20 poorly indicates cessation since many cases do not exhibit graupel long before cessation. The remaining two thermal levels (G10 and G15) show promise
as cessation indicators, with a majority of cases losing predominant graupel presence near cessation. However, similar to our reflectivity distributions (Fig. 4), there are several exceptions. Once again, implementing graupel presence without including additional parameters to forecast cessation would lead to lightning advisories that either last longer than needed or worse, are ended prior to cessation.

Testing cessation schemes will include identifying pairs of parameters that increase time savings and do not compromise safety. An example of a possible combination is shown in Fig. 6a, where red (blue) dots indicate that graupel was (was not) present at -10°C for individual cases. Starting 13 min after cessation, there are no cases with both reflectivity greater than 35 dBZ and graupel present at -10°C. This is a promising result, corresponding to PF15’s isolated cessation algorithm. However, some cases do exhibit values less than 35 dBZ and no graupel presence at 15 min before cessation. Even when combined, these two parameters may lead to advisories being ended too early.

The remaining panels in Fig. 6 combine additional cessation parameters (color coded) with R10 during the cessation period. Small MCCR values are observed in cases where R10 is > 35 dBZ after lightning cessation (Fig. 6b). When the decaying storm’s R10 values exceed 35 dBZ, it is presumed that the potential for a flash is increased. Therefore, because cessation has occurred, minimal MCCR may have prevented a later flash. Thus, MCCR may be a limiting factor for flash potential in cases with weakly connecting composite reflectivity between the active and decaying storms. No trends in 30D (Fig. 6c) or 30G (Fig. 6d) were observed relative to R10.

### 3.2 Cessation Percentages

We next examine reflectivity thresholds and graupel presence from a different perspective, calculating the percentages of cases at 1 min intervals when these conditions are met. Forecasters at the 45WS could use these percentages as a reference when deciding whether to end lightning advisories. Thresholds of 40 dBZ and 35 dBZ were tested for R5, R10, and R15. These thresholds are based on median values of the parameters at the time of cessation (Fig. 4), and they have been used in prior cessation studies (Preston and Fuelberg 2015; Stano et al. 2010; Anderson 2010). At 15 min after cessation (Fig. 7b), 36.8% of cases still exhibit R5 > 35 dBZ. Therefore, this threshold appears too strict to accurately represent the potential for future flashes.
At 15 min prior to cessation, the percentages are 60% for R10 > 40 dBZ (Fig. 7c), 45.7% for R15 > 40 dBZ (Fig. 7e), and 68.6% for R15 > 35 dBZ (Fig. 7f). These relatively small percentages prior to cessation do not exhibit a major change as cessation occurs. Thus, there is only a weak relationship between lightning cessation and the three thresholds. The thresholds R5 > 40 dBZ (Fig. 7a) and R10 > 35 dBZ (Fig. 7d) do show promise in indicating lightning cessation, due to their large changes during the cessation period. Their good performance may be attributed to the 40 dBZ and 35 dBZ thresholds corresponding to our median values of R5 and R10, respectively, at the time of cessation (Fig. 4). The percentages from 15 min before cessation to 15 min after cessation decrease from 82.8% to 10.5% for the 40 dBZ threshold at -5°C. For the 35 dBZ threshold at -10°C, the percentages from 15 min before cessation to 15 min after cessation decrease from 88.6% to 10.5%. The latter is the same threshold proposed by PF15 for isolated
Figure 7. Percentages of cases with a specified reflectivity threshold before and after cessation. For a), c), and e) the threshold is 40 dBZ for R5, R10, and R15, respectively. For b), d), and f) the threshold is 35 dBZ for R5, R10, and R15, respectively.

storms. It now outperforms the five other thresholds that we examined as an indicator of nonisolated lightning cessation. However, we recall PF15’s analysis that using this threshold will lead to lightning advisories being ended too early in some nonisolated cases—a dangerous situation.
Percentage analysis of the presence of graupel at different thermal levels is shown in Fig. 8. Graupel is still present at 0°C in 68.4% of the cases 15 min after cessation (Fig. 8a), indicating a lack of correspondence to cessation. However, in the time-integrated 15 min period prior to cessation, graupel still exists in 96.1% of the cases at 0°C. Although the G0 percentages do not decrease quickly after cessation, there is a strong probability that if no predominant graupel exists, cessation has occurred. Although this threshold would increase the safety of a cessation algorithm, it may limit the time savings of using this parameter. G5 exhibits similar, but even less useful results (Fig. 8b). G10 (Fig. 8c) and G15 (Fig. 8d) exhibit the greatest temporal gradient of graupel presence percentages during the cessation period. The G10 (G15) percentages change from 91.4% (80%) to 15.8% (5.3%) between 15 min prior to 15 min after cessation. PF15’s graupel parameter for isolated storms (G10) again outperforms the other four thermal levels of graupel presence we tested for nonisolated storms. G20 displays the greatest dichotomy during the cessation period. During most minutes after cessation, the HCA indicates no graupel at -20°C. The three colder thermal levels (G10, G15, and G20) show the most promise in predicting lightning cessation because of their greater changes during cessation. Unfortunately however, the changes in the percentages of both reflectivity thresholds and graupel presence are not abrupt during the cessation period. Nevertheless, the percentages of graupel presence and reflectivity thresholds give insight into our nonisolated cessation quandary.

Identifying crucial thresholds of horizontal reflectivity could help quantify a forecaster’s confidence that cessation has occurred. Reflectivity thresholds ranging from \( Z_H < 45 \) dBZ to \( Z_H < 26 \) dBZ are displayed for all five thermal levels in Fig. 9. We calculated the percentage of minutes that cessation had already occurred (time > 0 min) after the specified threshold was reached. For example, cessation had already occurred in 90% of the minutes after reflectivity at 0°C was less than 37 dBZ (Fig. 9a). One should recall that this calculation is based only on maximum reflectivity values 15 min prior to and after cessation. We consider these percentages to be strong indicators of the degree of confidence that cessation actually has occurred. A relatively large increase in cessation percentages is observed near the threshold of \( Z_H < 40 \) dBZ at the 0°C and -5°C thermal levels. Waiting for R5 to decrease from less than 41 dBZ to less than 36 dBZ leads to an increase from ~65% to ~90%, increasing the confidence that cessation has taken place. The percentage reaches 99.5% for R0 (R5) at \( Z_H < 28 \) dBZ (< 26 dBZ). Additionally, the percentage increases at the \( Z_H < 35 \) dBZ threshold for R10. The changes in
Figure 8. Percentage of cases with graupel before and after cessation for a) G0, b) G5, c) G10, d) G15 and e) G20.

percentages for R15 and R20 display a more linear increase, making them less useful. These percentages show the important reflectivity ranges at different thermal levels that may indicate cessation.
Figure 9. Percentages of minutes in which cessation occurred are plotted with the x axis representing reflectivity thresholds. Values for R0, R5, R10, R15, and R20 are colored black, red, green, gray and blue, respectively.

3.3 Skill Scores

We next test the performance of cessation algorithms using the dependent dataset. We later will present similar metrics for the independent dataset and compare the results. Similar to PF15, probability of detection (POD), false alarm ratio (FAR) and success ratio (SR) are utilized to test the effectiveness of our cessation algorithms. Hits, misses and false alarms are defined in Table 1.

Table 1. Definitions of hits, misses and false alarms in relation to lightning cessation and our lightning cessation schemes.

<table>
<thead>
<tr>
<th>Has cessation occurred?</th>
<th>Did our cessation algorithm end the advisory?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>yes</td>
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<tr>
<td></td>
<td>no</td>
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Has cessation occurred? yes no

Did our cessation algorithm end the advisory? yes hit false alarm

Hits occur when a lightning advisory is canceled after cessation has occurred (a safe outcome). A miss occurs when an advisory is never canceled while the storm is being tracked. False alarms are when a lightning advisory is ended prior to cessation. Since the size of our dataset decreases after cessation (Fig. 3), the number of misses will be artificially increased,
hindering the utility of the miss statistic. FAR is computed by dividing the number of false alarms by the sum of false alarms and hits. SR is defined as SR = 1 - FAR, with an SR of 1 indicating no false alarms. POD is computed by dividing the number of hits by the sum of hits and misses. The critical success index (CSI), which can be rearranged as a function of POD and SR, is calculated by dividing the number of hits by the sum of hits, misses, and false alarms.

Our 60 potential cessation algorithms utilized flash interval, distance measures, graupel presence, and reflectivity thresholds. We used a 10 min wait time since PR15 and Stano et al. (2010) found it to safely provide time savings (i.e., we ended a lightning advisory 10 min after certain conditions were met). Reflectivity schemes employed thresholds of $Z_H < 35$ dBZ and $Z_H < 40$ dBZ at R5, R10 and R15. Schemes based on the presence of graupel were evaluated at thresholds of G5, G10, G15, and G20. Both reflectivity and graupel schemes included combinations of their thresholds and each of our three new parameters (30D, 30G and MCCR). Since the 75th percentile of MCCR was at level four (22.5-25 dBZ) after cessation (Fig. 4f), that value was chosen as its threshold. After cessation, both 30D and 30G had a 25th percentile value of ~10 nm (~19 km) which we defined as the threshold for the distance parameters.

Figure 10. SR and POD for cessation schemes utilizing graupel (blue circle), reflectivity (red cross), combined graupel and reflectivity schemes (black X) and flash interval-based (green dash). Colored boxes indicate the scheme with the greatest CSI within each of the three groups. Dashed boxes indicate the greatest CSI for each of the groups with SR = 1.
Our ‘combined’ schemes incorporated pairs of graupel presence and reflectivity thresholds, while flash interval schemes paired either reflectivity or graupel thresholds with flash interval. Values of POD and SR for all of the potential cessation algorithms are plotted in Fig. 12. Schemes within each group having the greatest CSI are labeled with a box of the group’s respective colors (see panel on left side). Dashed boxes indicate the greatest CSI values for three groups in which the scheme had SR = 1.

Results indicate that the cessation algorithms incorporating flash interval (labeled green) perform better (greater CSI) than the other groups. The algorithms with the greatest CSI (0.711) required graupel absence at -15°C or R10 < 35 dBZ and no lightning flashes for a 5 min period. It is important to reiterate that flash interval schemes used a 5 min wait time, while all others used a 10 min wait time. The graupel scheme (labeled blue) with the greatest CSI (0.605) utilizes a 10 min wait time and graupel absence at -15°C. The reflectivity schemes (labeled red) with the greatest CSI (0.605) are R10 < 40 dBZ and R5 < 40 dBZ. A CSI of 0.658 is observed for the best ‘combined’ schemes (labeled black) that utilized graupel absence either at G20 or G15, paired with R10 < 40 dBZ. No scheme utilizing one of our three new parameters (MCCR, 30D, and 30G) achieves the greatest CSI in our four groups. The scheme including G15 and MCCR < 4 achieves the greatest CSI (0.579) of schemes that use one of the three parameters.

Unfortunately, even our best CSI value (0.711) for nonisolated cases is inferior to those of PF15 for isolated cases.

Since safety is the major concern for the 45WS, schemes with SR (FR) ratios of 1 (0) are desirable. These schemes provide maximum time savings without endangering lives and property. The safe (SR = 1) flash interval scheme that had the best CSI (0.474) required R5 < 35 dBZ and no flashes for 5 min. However, since longer (> 5 min) flash intervals have been observed (Stano et al. 2010), using this scheme for absolute safety is not recommended. The safe reflectivity scheme with the greatest CSI (0.263) utilizes reflectivity less than 40 dBZ at -5°C and 30G less than 10 nm (~19 km) for 10 min. The safe graupel scheme with the greatest CSI (0.342) utilizes graupel absence at -15°C and 30G less than 10 nm (~19 km) for 10 min. These two schemes achieve a success ratio of 1 using our new parameters. Thus, the inclusion of 30G in both schemes may indicate that the distance to the closest charging area (graupel presence at G10) is important in forecasting lightning cessation in nonisolated storms.
3.4 Application to Independent Dataset

We now evaluate our cessation algorithms on the independent dataset consisting of 12 cases during the 2013 warm season. Similar to our dependent dataset, the number of cases decreases 50% from the time of cessation to 15 min after cessation (Fig. 11). Three cases are removed just 1 min after cessation. The percentages of cases with certain reflectivity thresholds during cessation are shown in Fig. 12. Even with the relatively small dataset, these values generally are similar to those of our dependent data (Fig. 8), consistent with our previous findings. The parameters R5 > 40 dBZ (Fig. 12a) and R10 > 35 dBZ (Fig. 12d) again decrease greatly during the cessation period. The R5 (R10) percentages decrease 83.3% (91.7%) at t = -15 min to 16.7% (33.3%) at t = +15 min. Similar changes were apparent in the dependent dataset. Since this occurs in both datasets, the results may be helpful in forecasting nonisolated cessation. The percentages of R10 > 40 dBZ (R15 > 35 dBZ) (Fig. 12c (Fig. 12f)) also decrease considerably, from 66.7% (75%) to 0% (16.7%) during cessation. However, since both of their starting values are small, they are less likely to aid in cessation forecasting.

The percentages of independent cases having graupel at the five thermal levels are plotted in Fig. 13. Similar to the dependent dataset (Fig. 7), G10 and G15 exhibit the greatest decrease in percentages (91.7% to 33.3% and 66.7% to 0%, respectively) between t = -15 min and t = +15 min. G0 and G5 show the smallest decreases during cessation. The percentage for G15 steadily increases slightly after cessation. However, this is due to the decrease in dataset size affecting the percentage calculation. From 0 min to 14 min after cessation, only one case contains graupel...
at -15°C, while no case contains graupel at -20°C after cessation. Thus, there is a relationship between graupel presence at colder thermal levels and lightning cessation, consistent with the results of the dependent data (Fig. 9).

Figure 12. As in Fig. 7, but for the independent dataset.

The percentage of minutes for which cessation has occurred is plotted for different reflectivity thresholds in Fig. 14, similar to Fig. 11 of the dependent data. The R5 and R0
percentages again are the only thresholds that reach 99.5%. Both achieve this percentage at the same threshold as the dependent dataset, suggesting that they could be used as a cessation parameter. Nonetheless, they may not provide time savings over the 30/30 rule. The remaining reflectivity values (R10, R15, and R20) exhibit major differences compared to the dependent data (Fig. 11). The R10, R15, and R20 percentages do not increase rapidly at any thermal level (black, red and green bars in Fig. 14, respectively). The percentages also do not reach 90% at
any reflectivity threshold, as they did in the dependent dataset. This major difference indicates that reflectivity prior to cessation is skewed toward decreased reflectivity in the independent dataset. This difference in results between the two dataset samples suggests that R10, R15, and R20 may not be useful parameters using this analysis.

Figure 14. As in Fig. 9, but for the independent dataset.

Skill scores for the independent dataset were computed for all 60 cessation schemes. The results in Fig. 15 are presented using the format of Fig. 10. Flash interval (green) algorithms again perform best, with G20 and R5 < 40 dBZ producing the greatest CSI (0.750). However the best performing choices differ, since the CSI of the dependent dataset’s best performing schemes paired flash interval with G15 or R10 < 35 dBZ. The combined (black) and reflectivity (red) schemes in the dependent dataset exhibit the next greatest CSI (0.600). These schemes include R5 < 40 dBZ alone and paired with G15 or G20. The graupel scheme with the greatest CSI (0.500) was G15. The similar values and hierarchy of the four types of algorithms are consistent with results from the dependent dataset. However, no scheme produces SR = 1 (zero false alarms), which did occur in the dependent dataset. The lone false alarm in several of the cessation schemes is due to the same case. The flash interval scheme with R5 < 40 dBZ, the graupel scheme of G10 with 30G, and the reflectivity scheme of R5 < 40 dBZ with 30G
produced zero false alarms in the dependent dataset but one false alarm in the independent dataset. If this one false alarm (out of 50 combined cases) had not occurred, these three schemes would safely end advisories in all cases.

Figure 15. As in Fig. 10, but for the independent dataset. However, dashed boxes now indicate the maximum SR for each of the groups since there were no schemes with SR =1.

The problematic case that caused the one false alarm occurred on 30 August 2013 (Case 58). The composite reflectivity, LDAR lightning channels, LDAR initiation points, and NLDN polarity-specified CG of the last flash are shown in Fig. 16a. Values of HCA at -10°C and the contour levels of MCCR are displayed in Fig. 16b. The last flash (last to traverse over the decaying storm’s 30 dBZ contour) initiated outside of the decaying storm at 2020 UTC. The maximum connecting composite reflectivity at cessation was 17.5-20 dBZ (level 2), and the values of 30D (30G) were measured at 11 nm (20 km) (15 nm (~28 km)). The location of initiation occurred within the 30 dBZ contour of stratiform precipitation associated with the active storm. We hypothesize that the initiation of this flash, in an area devoid of predominant graupel, may have occurred due to charge advection, residual charge, or the fact that limited graupel was still present, leading to noninductive charging.
Figure 16. Properties of Case 58 from 30 August 2013 at 2020 UTC, the time of last flash. a) WDSS-II merged composite reflectivity (dBZ) from KTBW and KMLB with labeled colorbar at top of the figure. LDAR-II flashes are marked using thin white lines, with green diamonds indicating initiation locations. Negative NLDN CG strikes are marked in light green. The active (decaying) storm is indicated by a blue (red) arrow. b) WDSS-II merged HCA values at -10°C are colored, with graupel marked as pink and dry ice is marked in light blue. The red lines represent seven levels of composite reflectivity, with values ranging from 15-30 dBZ at 2.5 dBZ intervals.

Vertical cross sections of reflectivity along the paths of lightning flashes are shown in Fig. 17b. The direction of each arrow indicates the orientation of the cross sections. The anvil
consists of the weak composite reflectivity region between the decaying storm and the active storm where reflectivities vary from 15-25 dBZ near 23 kft (~7km). A troubling observation is seen in Fig. 18. Not only does the flash extend from the active cell to the decaying cell through weak reflectivity (as small as 10 dBZ), but the LDAR-II data show paths that approach the surface (~3000 ft (~1km)) at several locations. These flashes pose a threat for ground operations at KSC.

Figure 17. (Top panels) WDSS-II merged reflectivity (dBZ) from KTBW and KMLB with labeled colorbar at the top of each panel. Horizontal distances (nm) and heights (kft) are labeled. (Bottom panels) Corresponding locations of the cross sections. LDAR-II flashes are marked using thin white lines, with green diamonds indicating initiation locations. All flashes binned during the minute of the last flash Negative NLDN CG strikes are marked in light green.

Figure 18. All flashes binned during the minute of the last flash of Case 58 on 30 August 2013 at 2020 UTC. The x-axis is orientated from northeast (left) to southwest (right), while the y-axis is in the vertical. WDSS-II merged composite reflectivity (dBZ) from KTBW and KMLB is shown with labeled colorbar at the top of the figure. LDAR-II flashes are marked using thin white lines, with green diamonds indicating initiation locations. Negative NLDN CG strikes are marked in light green.
Electric field mill data may indicate the potential for electrical interaction between storms. The KSC Advanced Ground Based Field Mill network measures the electric field strength (V m\(^{-1}\)) surrounding KSC/CCAFB. Murray et al. (2004) used the data to explore the electric field values of debris clouds, using the definition from Krider et al. (1999): “any cloud, except an anvil cloud, that has become detached from a parent cumulonimbus cloud or thunderstorm, or that results from the decay of a parent cumulonimbus cloud or thunderstorm.” Their results showed that 5% of reflectivity bins, in which the column reflectivity was less than 5 dBZ, exhibited a field strength > |1| kV m\(^{-1}\). Nonisolated Case 58 was not located within the field mill network. However, Fig. 19 shows a different case (Case 30) that did not lead to an unexpected flash from an active (blue arrow) to a decaying storm (red arrow). No flash occurred even though a large magnitude electric field (~ |4| kV m\(^{-1}\)) was observed in the decaying storm ~10 min after the last flash. Why did a flash occur in Case 58 but not Case 30? Both cases had active storms within a ~10-20 nm (~19-37 km) range of the decaying storms, with similar reflectivities connecting the storms. We cannot answer this question with the data that are available. However, one difference between the two cases is that the active storm in Case 58 was much larger in horizontal extent than in Case 30.

Figure 19. Plan view showing properties of Case 30 at 2205 UTC on 11 July 2013, 9 min after the last flash. a) WDSS-II merged composite reflectivity (dBZ) from KTBW and KMLB. The active (decaying) storm is indicated by a blue (red) arrow. LDAR-II flashes are marked using thin white lines. Negative NLDN CG strikes are marked in light green. b) Electrical potential gradients (V m\(^{-1}\)) at 30 KSC field mill sites, where the value is colored according to the color bar. Values are superimposed on a Google earth image.
We examined 50 cases (38 dependent, 12 independent) of nonisolated lightning cessation and tested 60 potential algorithms for estimating whether cessation had occurred. Our definition of “nonisolated” required one storm that apparently had produced its last flash, being connected by a composite reflectivity region $\geq 15$ dBZ to a one (or more) storms still producing flashes. Other requirements included the decaying storm retaining its 30 dBZ composite core. We analyzed radar-derived storm characteristics between 15 min prior to and 15 min after cessation. Our results supplement PF15’s findings for forecasting cessation of isolated storms. However, our results confirm that forecasting nonisolated cessation is more complex than forecasting isolated cessation.

The research leads to several key conclusions that could aid in forecasting lightning cessation for warm season storms in Florida. Although our findings showed a relationship between reflectivity, graupel, and nonisolated lightning cessation, not all cases matched our expectations. Values of reflectivity and graupel presence do not always follow idealized principles, both before or after cessation.

Important conclusions can be drawn from our cessation percentages of various parameters and thresholds. In an operational setting, percentage values of some parameters can supply information about the potential risk of an additional flash. Based on the analysis of our dependent dataset and confirmation of results in the independent dataset, parameters G10, G15, R10 $> 35$ dBZ, and R5 $> 40$ dBZ are recommended for operational use since they display the greatest change in percentages during the cessation period. Of the 482 min of data accumulated after cessation, only 11 min (2.2%) contained predominant graupel at -20°C. Therefore, graupel absence at -20°C may be used as a cautionary rule. If graupel does exist at -20°C, it is not safe to end the advisory. If graupel is not present, one should still refer to additional parameters in making this decision. In both our independent and dependent datasets, $> 99.5\%$ of minutes with R5 $< 28$ dBZ (R0 $< 30$ dBZ) already had experienced cessation. Thus, when either of these thresholds is reached, our limited dataset indicates that a forecaster could safely end a lightning advisory with $\sim 99.5\%$ confidence. This value of confidence must be confirmed on a larger dataset.
None of the 60 cessation algorithms ended lightning advisories in all cases with zero false alarms. However, waiting 5 min after a flash and R5 > 40 dBZ was no longer observed led to only one case (Case 58) having a false alarm. This scheme produced a CSI of 0.750 (0.684) in the independent (dependent) dataset. Results showed that using flash interval in a cessation scheme can increase hits with minimal false alarms. However, since Stano et al. (2010) found flash intervals greater than 20 min, caution must be exercised when using short intervals (< 25 min), such as the 5 min we employed.

We believe that the safest algorithm (not using flash interval) is waiting 10 min after R5 > 40 dBZ combined with 30G thresholds are no longer observed. This pairing produced the same, single false alarm (Case 58) in our independent dataset with no false alarms in the dependent dataset. The scheme yielded had a CSI of 0.400 (0.342) in the independent (dependent) dataset. Several other schemes also only produced one false alarm in the independent dataset and no false alarms in the dependent dataset. G10 with 30G yielded a CSI of 0.2 (0.263), R5 < 40 dBZ with 30D yielded a CSI of 0.3 (0.211), and G10 with 30D yielded a CSI of 0.2 (0.184) in the independent (dependent) dataset. Using these algorithms to end advisories will decrease wait times while greatly limiting the potential for unexpected flashes after the advisory is ended.

Our three new parameters (30D, 30G, and MCCR) by themselves failed to indicate nonisolated cessation. However, 30G did perform well when combined with other parameters, appearing in two of our safest cessation algorithms (not including flash interval). The distance between active and decaying storms may influence the chance of a flash. If the distance between storms increases, the charge gradient required for a flash to traverse from the active to the decaying storm also may increase. Greater safety is observed with cessation algorithms that include 30G paired with other parameters. This distance shows promise in performing as a limiting factor when forecasting lightning cessation.

The physical reason why radar-derived parameters did not consistently indicate lightning cessation in our dataset is still unknown. Storms at different stages of their lifetimes may have oppositely charged layers at similar vertical levels. Sea breeze circulations could lead to charge advection from active storms to decaying storms. Finally, remnant charge (E values) in decaying storms may be strong enough to produce a flash from active storms. These increases in electric field gradient may aid in producing lightning flashes between storms.
Most important to future work is a larger dataset of both isolated and nonisolated cases. A greater number of nonisolated case ‘outliers’ may give insight into why they occur and what causes their atypical reflectivity and graupel values during the cessation period. This study did not observe any factors that differentiate all storms that produced unexpected flashes. Additional nonisolated cases that are located within the field mill network at KSC/CCAFS may provide insight into lightning interaction between active and decaying storms. However, this will be difficult since few storms decay within the relatively small network. Field studies that relate electrical soundings with radar-derived microphysical data could quantify microphysical differences between nonisolated and isolated storms. They could indicate percentages of trailing anvil structures that contain sufficiently large E values to produce flashes between storms. High-resolution (< 2 km) numerical modeling of specific cases also could increase our understanding of nonisolated cessation. Finally, dual-Doppler radar data would allow the calculation and examination of parameters requiring vertical motion, such as graupel flux. These future endeavors may lead to a better understanding of nonisolated lightning cessation.
REFERENCES


Gremillion, M. S., and R. E. Orville, 1999: Thunderstorm characteristics of cloud-to-
ground lightning at the Kennedy Space Center, Florida: A study of lightning initiation
signatures as indicated by the WSR-88D. Wea. Forecasting, 14, 640–649,

Paxton, 1992: Cloud-to-ground lightning related to deaths, injuries, and property damage
in central Florida. Proceedings, International Conference on Lightning and Static
Electricity, October 6-8, Atlantic City, NJ, FAA Report No. DOT/FAA/CT-92/20, 66-1-
66-11.

——, ——, and C. Zimmermann, 1999: Updated recommendations for lightning

Huffines, G. R., and R. E. Orville, 1999: Lightning ground flash density and

Jayaratne, E. R., C. P. R. Saunters, and J. Hallett, 1983: Laboratory studies of the
charging of soft hail during ice crystal interactions. Quart. J. Roy. Meteor. Soc., 109,

Jensenius, J. S., Jr, 2014: A Detailed Analysis of Recent Lightning Deaths in the United
States, paper presented at 5th International Lightning Meteorology Conference, Tucson,
Ariz.

Krehbiel, P. R., 1986: The electrical structure of thunderstorms. The Earth’s Electrical
Environment, Geophysics Study Committee, Studies in Geophysics, National Academy
Press, 90–113.

Kuhlman, K. M., D. R. MacGorman, M. I. Biggerstaff, and P. R. Krehbiel, 2009:
Lightning initiation in the anvils of two supercell storms, Geophys. Res. Lett., 36,

Lakshmanan, V., K. Hondl, and R. Rabin, 2009: An efficient, general-purpose technique
for identifying storm cells in geospatial images. J. Atmos. Oceanic Technol., 26,

using polarimetric variables. J. Atmos. Oceanic Technol., 31, 1234–1249,

——, and T. Smith, 2009: Data mining storm attributes from spatial grids. J. Atmos.


——, ———, P. R. Krehbiel, N. R. Lund, and C. R. Maggio, 2009: Electrical evolution during the


BIOGRAPHICAL SKETCH

Matthew J. Davey was born on August 26th, 1992, growing up in Cranston, RI. He is one of four Davey brothers (Pete, Pat and Chris) who were always in sync, leading to many summers filled with backyard sports. My mother, (Kathryn) raised us from boys to men, while excelling at her fulltime job, teaching music. Matthew’s interest in business stemmed from his admiration of his father (Peter), who went from window washer to successful business owner. Matthew’s memorable childhood accomplishments include playing in the Little League World Series, running a neighborhood car wash service, and winning several Catholic league basketball state championships at his primary school, Cranston-Johnston Catholic Regional (CJCR). Matthew attended Bishop Hendricken High School, where he enjoyed singing in choir, playing soccer, and performing in musicals. His favorite memory was when he, along with a few good men, beat our rival La Salle (a nationally ranked team) in the state semifinals. Even though they lost in the championship, Matthew intends brag to his grandkids about how he played through a broken scapula.

Originally, Matthew chose the ‘TV’ meteorology track at Lyndon State College, hoping to follow in the footsteps of the famous alumni Jim Cantore and Tony Petrarca. However, Dr. Jason Shafer introduced Matthew to the financial, energy, and business sectors of meteorology. Matthew changed paths, choosing to utilize his mathematical skills and interest in business. While working as a Resident Assistant, Pubic Safety Worker, and Supplemental Instructor, he graduated with a Meteorology major, Applied Mathematics major, and a Business Minor. During his time at Lyndon State, Matthew was selected to participate in NASA’s Student Airborne Research Program in California. This inspired him to attend graduate school. He met Dr. Henry Fuelberg, SARP’s mission meteorologist, and later selected him (FSU) for his graduate advisor. In the summer of 2014, Matthew began working for Jim Roemer, a meteorologist who trades commodities. He has accepted a full-time position with him after graduation and is very excited to learn more about the commodity market.