Improving Lightning Cessation Guidance Using Polarimetric Radar Data

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ABSTRACT

Polarimetric radar data are used to develop lightning cessation guidance for the Cape Canaveral area of central Florida. For this purpose, 80 nonsevere thunderstorm cells in 2012, mostly during the warm season, are analyzed. In-cloud and cloud-to-ground lightning data for the storms are obtained by combining information from the second-generation Lightning Detection and Ranging (LDAR-II) network and the National Lightning Detection Network (NLDN). Storms are tracked using the Warning Decision Support System–Integrated Information (WDSS-II) software, producing time series of radar- and lightning-derived parameters. The 80 storms are split into two categories: 1) 50 isolated storms whose lightning initiation sources are confined to the core or anvil region of the storm and 2) 30 nonisolated cells whose lightning channels are initiated in a nearby active storm and extended to the dissipating study cell. Trends in polarimetric radar parameters at different temperature levels are studied for 40 of the 50 isolated storms to develop cessation guidance. Results based on a completely independent sample of 10 storms reveal that the best-performing cessation algorithm utilizes the presence of graupel and horizontal reflectivity $\geq 35$ dBZ at the $\sim 10^8$ temperature altitude. Lightning is not expected 10 min after both thresholds are no longer met. However, this relationship does not apply to nonisolated cells because a neighboring storm could still be electrically active. Results show that a stratiform cloud region connecting the decaying storm to an active storm might facilitate further channel propagation that might not have occurred otherwise. Thus, the proposed cessation guidelines are not recommended for nonisolated cells.

1. Introduction

Lightning is the third-leading cause of storm-related deaths in the United States, ranking behind flash flooding and tornadoes (National Weather Service 2012; Roeder 2012). Forecasting the first and last flash of a storm is important because most lightning-related casualties occur before or after the most intense period of lightning activity when the threat is not as evident (Holle et al. 1992). The U.S. Air Force’s 45th Weather Squadron (45WS) issues lightning advisories for Florida’s Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS). Lightning is a major operational concern of the 45WS, because central Florida has the greatest flash density in the United States (Orville and Silver 1997; Huffines and Orville 1999; Rudlosky and Fuelberg 2011).

Lightning initiates between oppositely charged regions of a cloud, between clouds, or between the cloud and the earth’s surface. The noninductive charging (NIC) mechanism proposes that charge transfer within the updraft of a storm is due to collisions between ice crystals and graupel in the presence of supercooled water (e.g., Takahashi 1973; Jayaratne et al. 1983; Saunders et al. 1991). Charge separation and its vertical transport often produce a tripole charge structure characterized by 1) a weak positive charge region near $0^\circ$C, 2) a dominant negative layer between $-10^\circ$ and $-20^\circ$C, and 3) a positive region at even higher altitudes (Krehbiel 1986; Williams 2001). Relatively small ice crystals tend to be lofted upward to form the positive region, while larger, heavier graupel pellets settle to form the main negative region (Takahashi et al. 1999; Saunders et al. 2006; Akita et al. 2011). Recent studies (e.g., Stolzenburg et al. 1998; Bruning et al. 2010, 2014) have found that the charge structure of some storms is more complex than is portrayed by the prototypical tripole configuration. That is, different thermodynamic environments can affect the local charge structure in a storm (Williams et al. 2005).
Nonetheless, graupel–ice collisions in the mixed-phase region (from 0° to −20°C) of the updraft core are an essential ingredient in electrifying storms (Dye et al. 2000; Bruning et al. 2012). Thus, studying polarimetric radar data at temperature levels in the mixed-phase region should be a good proxy for storm electrification, regardless of charge complexity.

Considerable research has described the radar-derived characteristics associated with a storm’s first flash (e.g., Gremillion and Orville 1999; Wolf 2006; Woodard et al. 2012). However, much less research has considered lightning cessation (i.e., when a storm’s last flash has occurred). Carey et al. (2009) and Schultz et al. (2013) examined radar differential phase signatures and the vertical alignment of ice crystals as cessation neared. Seroka et al. (2012) studied vertically integrated ice and the timing of in-cloud (IC) and cloud-to-ground (CG) flashes in relation to lightning cessation. Additionally, Stano et al. (2010) developed cessation guidance for KSC, finding that the maximum interval (i.e., the greatest time between any two consecutive flashes of a storm) was a useful parameter. The majority of their storms had a maximum interval less than 10 min, biasing their schemes toward small intervals. However, storms with large maximum intervals pose the greatest threat to safety. These storms exhibit an apparent cessation, often exceeding 10 min, but then unexpectedly produce one or more additional flashes.

The 45WS does not end their lightning advisories as accurately as they initiate them (Roeder and Glover 2005), currently waiting ~20 min if there has been no lightning within a 5 nautical mile (n mi; 1 n mi = 1.852 km) radius of a region before ending an advisory. During a space launch, the wait time is increased up to 30 min within a 10 n mi radius of the vehicle flight path for extra safety (McNamara et al. 2009). After-the-fact analyses indicate that many advisories remain in effect longer than necessary. The 45WS would benefit from ending advisories earlier as long as safety is not compromised. The aviation industry, sports venues, and other outdoor interests also would benefit from improved cessation guidance.

Many outdoor interests use the well-known 30–30 rule for lightning safety (e.g., Holle et al. 1999) whose second component means waiting at least 30 min after no lightning has occurred before resuming outdoor activities. The present study seeks to safely shorten the 30-min wait time, as well as the wait time presently used by the 45WS.

Recent advances in lightning detection and radar technology are providing new insights about the occurrence of IC and CG flashes and their relation to storm-scale processes. The goal of this study is to develop statistically derived cessation algorithms based on polarimetric radar data and the timing of total lightning (IC and CG) that forecasters could employ operationally to safely end advisories earlier. The statistical guidance is based on NIC theory. Charge dissipation is the underlying concept for the wait-time approach presently used by the 45WS (W. Roeder 2012, personal communication) and is the approach that is further examined here.

We examine radar and lightning characteristics during the period leading up to and just after the last flash of a storm. Although graupel appears to be a necessary ingredient for a storm to be electrically active, we know of no previous study that has addressed the operational use of polarimetric-derived graupel information for last flash guidance. We use the presence of graupel at different temperature levels in the mixed-phase region (i.e., 0°, −10°, and −20°C) as a proxy for storm electrification. The polarity of graupel largely depends on the relative growth rate of the rebounding graupel–ice collisions (Emersic and Saunders 2010). Graupel pellets can charge positively at temperatures warmer than the reversal temperature (Jayaratne et al. 1983; Saunders et al. 1991; Takahashi et al. 1999; Kuhlman et al. 2006). Nonetheless, graupel in the mixed-phase region of an updraft core is a crucial ingredient in electrifying storms, regardless of the charging polarity (MacGorman et al. 2008).

Once a polarimetric parameter (e.g., horizontal reflectivity, differential reflectivity, correlation coefficient, etc.) becomes less, and remains less, than a prescribed threshold, we wait a certain amount of time (e.g., 5, 10, or 15 min) before ending the simulated advisory. That is, we are not attempting to forecast the time of a storm’s last flash but rather when no additional lightning is reasonably expected and the advisory can be safely canceled. We seek to find which combination of parameters, parameter thresholds, and wait times performs best in determining lightning cessation for nonsevere, single-cell thunderstorms in the KSC–CCAFS area.

2. Data and methodology

a. Lightning data

Total lightning information was obtained from the second-generation Lightning Detection and Ranging (LDAR-II) network at KSC–CCAFS (Fig. 1; Lennon 1975; Poehler and Lennon 1979; Maier et al. 1995; Britt et al. 1998; Boccippio et al. 2001; Roeder 2010). LDAR-II detects in three-dimensional space the very high–frequency (VHF) radiation that is emitted as a lightning channel propagates. The VHF sources from IC flashes and the upper portions of CG flashes are sensed with
a detection efficiency greater than 90% within 100 km of the network’s center (Boccippio et al. 2001). We merged LDAR-II data with CG flash data from the National Lightning Detection Network (NLDN; Orville 2008) since NLDN detects ground strike locations that LDAR-II usually does not provide. The NLDN has a typical detection efficiency of 90%–95%, and a mean location accuracy of ~500 m (Cummins and Murphy 2009).

Flash consolidation algorithms combine individual VHF sources into flashes by reconstructing IC channels and the upper portions of CG flashes (Lakshmanan et al. 2007b). The University of Oklahoma and the National Severe Storms Laboratory (NSSL) developed a flash consolidation algorithm, described by MacGorman et al. (2008), that is a component of the Warning Decision Support System–Integrated Information (WDSS-II) software (Lakshmanan et al. 2007b). The algorithm consolidates the sources based on user-defined thresholds and error ellipses that vary with range from the center of the LDAR-II network. We used the default spatial threshold settings of the algorithm and prescribed a 300-ms temporal constraint between individual sources. Previous studies have differed on the number of sources required to define a flash (e.g., Williams et al. 1999; Lang et al. 2004a; Schultz et al. 2009). We specified that all flashes must contain at least three individual sources to account for the lower detection efficiency of the LDAR-II network compared to the Oklahoma Lightning Mapping Array (Rudlosky and Fuelberg 2013), and to avoid the creation of singletons and flashes consisting of only two sources (Nelson 2002). Flashs with two or fewer sources are most likely related to noise. Because all of the nonsevere storms in our dataset exhibited only moderate flash rates (flash interval ≥1 s), we believe that the derived flash channels are suitable for this research (MacGorman et al. 2008). Flashs and sources were binned at ~1-min intervals so that our lightning data matched the temporal resolution of the radar data (see section 2b). New features of the flash consolidation algorithm allowed us to identify the location and time of each flash’s first source, denoted the initiation source. We defined the time of cessation as the time of the initiation source composing a storm’s last flash.

b. Radar and environmental data

The WDSS-II software allowed us to merge WSR-88D S-band polarimetric radar data from Melbourne (KMLB) and Tampa Bay (KTBW), Florida, for storms near KSC–CCAFS (Fig. 1). The merging algorithm (w2merger; Lakshmanan et al. 2006) blended data from the two radars at ~1-min intervals by weighting the contributions from each using an exponential function.
based on distance from the radar. WDSS-II does not wait until a volume scan is completed. Instead, it processes data from each incoming elevation angle and continuously updates and interpolates the data onto a three-dimensional Cartesian grid (Lakshmanan et al. 2006). We employed ~1-km horizontal and vertical grid spacing. The vertical resolution of 1 km has been used in previous studies (e.g., Gauthier et al. 2006; Melvin and Fuelberg 2010; Mosier et al. 2011). It is important to note that we ran a quality-control algorithm (w2qcm; Lakshmanan et al. 2007a) that accounts for beam blockages and removes areas of ground clutter from radar elevation scans before merging the radar data.

We used archived model analyses from the National Centers for Environmental Prediction Rapid Refresh (RAP) model (Benjamin and Sahm 2012) to describe the storm environments. Hourly RAP analyses were obtained at 13-km horizontal grid spacing and 50 vertical levels from archives of the Atmospheric Radiation Measurement Program. The RAP model analyses and the w2merger algorithm were used to interpolate the polarimetric products to the 0°, −10°, and −20°C temperature altitudes that are crucial to storm electrification. Trends in horizontal reflectivity $Z_H$, as well as various polarimetric parameters at these three temperature levels, were analyzed for storms near the end of their lightning activity.

We also used the WDSS-II hydrometeor classification algorithm (HCA) originally developed by J. Krause at the NSSL and described by Schuur et al. (2003), Ryzhkov et al. (2005), and Park et al. (2009). The algorithm uses polarimetric base products, reflectivity information, as well as two texture products: standard deviation of horizontal reflectivity std dev($Z_H$) and standard deviation of differential phase shift std dev($\Phi_{DP}$), which characterize the magnitude of small-scale fluctuations of $Z_H$ and $\Phi_{DP}$, respectively, along the radar beam. Studies that have discussed polarimetric radar data within the context of hydrometeor identification include Doviak and Zrnic (1993), Bringi and Chandrasekar (2001), and Kumjian (2013). Since HCA uses a fuzzy logic scheme with six input polarimetric radar variables (both single- and dual-polarization base data), it describes hydrometeor classification better than individual polarimetric parameters. The HCA identifies hydrometeor types and assigns a particle identification (PID) value to the dominant or majority quantity within each radar range gate of a volume scan (Woodard et al. 2012). As with the other polarimetric parameters, WDSS-II interpolated the PID categories to ~1-km horizontal and vertical grid spacing. However, in the case of two radar datasets being merged (as done here), the PID category at a location is the value from the closest radar, not the weighted contribution from each radar. The HCA allowed us to identify the types of hydrometeors in the mixed-phase region of a storm’s core. Since NIC theory suggests that the vertical distribution of hydrometeors is related to the charging mechanisms needed for electrification, we expected the HCA to play a key role in cessation guidance.

Figure 2 compares $Z_H$ and HCA products based on using a single radar (KMLB; Figs. 2a,c) and dual radars (KMLB and KTBW; Figs. 2b,d). The location of this storm (solid white circle; Fig. 1) is much closer to the KMLB radar than KTBW. Since HCA chooses the closest observation to the radar, the classification for this storm is almost always based on KMLB data unless its data are missing. Therefore, Figs. 2a and 2b exhibit little difference in classification except when a study cell propagates close to the KMLB radar (not shown). The $Z_H$ data (Figs. 2c,d) exhibit greater differences because an exponential weighting scheme is used when two radars are employed. Figure 2c shows an example of the storm top getting cut off when only KMLB radar data are used, with the missing data being filled in when KTBW is added (Fig. 2d).

c. Storm selection and tracking

Selecting the storms for the dataset was a multistep process. To make the selection easier, only 19 different days during 2012 with many lightning-producing storms were explored. These days mostly occurred during the warm season (May–September). Although hundreds of storms on these days were considered, most were rejected because they did not satisfy additional criteria. The storms had to be single cells within 100 km of the center of the LDAR-II network near KSC–CCAFS. Many of the rejected storms either moved outside the 100-km radius during their lifetime or could not be tracked as a coherent feature because they merged with nearby storms. Of the storms examined (Table 1), 80 ultimately satisfied all the criteria. None had recorded severe weather reports (Johnson et al. 1998). To reduce the chance of having a biased dataset, the storms were selected prior to examining the polarimetric-derived hydrometeor types in the core of each storm.

The K-means storm clustering and tracking algorithm within WDSS-II (w2segmotionl; Lakshmanan et al. 2009; Lakshmanan and Smith 2009) was used to track the 80 storms. This algorithm was implemented after data from the two radars were already merged. The tracking procedure was automated, producing a database at 1-min intervals that described the lightning and radar characteristics during the storm’s lifetime. Information about these tracked storms was then extracted from the database. It was important to fine-tune
the K-means options to ensure that the storms to be studied were sufficiently separated from any nearby storms. We tracked each storm using two parameters: vertically integrated liquid density and dilated composite reflectivity. A description of the dilation procedure is given in Lakshmanan (2012). We chose the storm track based on which of the two tracking parameters performed best during the later part of the storm’s lifetime. A detailed description of the clustering algorithm can be found in Lakshmanan et al. (2009). As a final step, all 80 selected storms were examined visually to ensure that their core was isolated and tracked consistently. Figure 3 shows an example storm and its corresponding WDSS-II gridded output at 1833 UTC 7 May 2012.

d. Separating storms based on lightning initiation locations

We defined an isolated storm as one separated from nearby electrically active storms by an area of composite $Z_{H1} < 15$ dBZ. This criterion was used because we observed no lightning channels traversing areas of $Z_{H1} < 15$ dBZ between our study cells to any adjacent cell. Of the 80 storms examined, 50 had lightning initiation sources confined to their core or anvil regions. All 50 of these storms were isolated, making it easy to assign a flash to the storm being studied. Thus, we expected parameter values within the storm’s core to be related to the time of cessation. This is consistent with previous studies (e.g., Melvin and Fuelberg 2010; Stano et al. 2010).

The 30 remaining storms developed in clusters or broken lines along the sea-breeze front or an outflow.

<table>
<thead>
<tr>
<th>Month</th>
<th>No. of storm cells</th>
<th>No. of storm days</th>
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<tbody>
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<td>February</td>
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<td>1</td>
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<tr>
<td>March</td>
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<td>July</td>
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boundary as is commonly observed in Florida. Near the time of dissipation, the study cells became embedded in a stratiform precipitation area that connected them to a nearby active storm. Thus, these study cells were not isolated (Lund et al. 2009). We defined the stratiform region as being a nearly contiguous region of composite \( Z_H \geq 15 \, \text{dBZ} \) (Biggerstaff and Houze 1991; Loehrer and Johnson 1995). The area of the connecting region of \( Z_H \geq 15 \, \text{dBZ} \) varied, but typically ranged from 100 to 2000 km\(^2\). In spite of the connecting stratiform region, the core of each study cell remained completely separate from neighboring cores, enabling it to be tracked using WDSS-II. At least one flash involving these nonisolated study cells was initiated in the nearby storm during the study cell’s lifetime. This electrical interaction between cells has been observed in previous studies. For example, Lund et al. (2009) observed flashes in a mesoscale convective system (MCS) spanning more than one cell and propagating into stratiform regions. In our case, the final flash in 27 of the 30 nonisolated study cells initiated outside these cells in a nearby storm that was not part of our dataset. The final flash of the three remaining cells initiated inside the core of the study cell. However, every nonisolated cell had at least one IC or CG flash that originated in a nearby cell and traveled within a region of \( Z_H \geq 15 \, \text{dBZ} \) to the study cell. The disparity between the locations of the 30 embedded cell cores and their lightning initiation sources made it especially difficult to develop cessation guidance for them. Therefore, we did not use them in developing our cessation algorithms. The results presented in section 3 focus on the 50 isolated storms. The cessation characteristics of the 30 embedded (nonisolated) cells are examined in section 4.

e. Canceling the lightning advisory

We did not attempt to end a lightning advisory over a specific area as is commonly done by the 45WS (Roeder et al. 2003). Instead, we focused on storm-based guidance by continuously following each storm until cessation, using the K-means tracking algorithm. We visually checked the storm track and flashes associated with the storm to make sure they were correct. Once a storm had dissipated (i.e., no remaining distinct core), we continued to monitor residual areas with composite \( Z_H \geq 15 \, \text{dBZ} \) to ensure that no further flashes occurred.

f. Cross validation

Of the 50 isolated storms examined, 10 were randomly selected as our independent sample and used only for performance testing in section 3e. With a dependent sample size of 40 isolated storms remaining, we first demonstrate that our cessation algorithms are not sensitive to or biased by this relatively small sample. A fourfold cross-validation technique was used for this purpose (Wilks 2011; Moore 2014). In the first iteration, we randomly categorized the 40 storms so that 30 (training set) were used to develop the statistical cessation algorithms and the remaining 10 (test set) were used to estimate future forecasting performance (Wilks 2011). During the second iteration, this procedure was repeated with the same 40 storms, but the 10 storms used for verification in the first iteration were excluded from being used again as verification. Instead, they became part of the training set. This process was repeated four times so that all 40 storms were used once as verification. This cross-validation technique maximizes our limited sample size and helps prevent overfitting.

3. Characteristics of the isolated storms

a. Radar products at different temperature levels

We first examined maximum \( Z_H \) at environmental temperatures of 0°C, −10°C, and −20°C. Pearson correlation coefficients \( R \) and linear slopes between \( Z_H \) and the time of cessation were computed. Results at the −10°C level were found to be better than those at the other two temperatures (not shown) based on steeper slopes and greater \( R \) values. Figure 4 shows maximum \( Z_H \) at −10°C at 1-min intervals for the 30 training storms in each of the four cross-validation groups. Root-mean-square errors (RMSEs) between observed and predicted values were computed on the 10 test storms not used during the regression fitting process. The small range of RMSE
values (inset, Fig. 4) shows that the four regression lines perform similarly on the independent data.

We then compared the regression lines using MATLAB’s one-way analysis of covariance (ANOCOVA) package, which assesses whether slopes and intercepts for the four groups are comparable. Results indicate that the four regression lines have a mean slope (storm decay rate) of \(-0.36 \text{ dB} \text{Z}^{-1}\) and a mean intercept (\(Z_H\) at time \(t = 0\)) of 35.7 dB, with only small differences among the groups (Fig. 4). Additional statistical tests revealed no significant differences in slopes among the four groups.

The similar storm decay rate (\(-0.36 \text{ dB} \text{Z}^{-1}\)) among the cross-validation groups suggests that a storm in group 1 could just as easily have been in group 2, and vice versa; the same is true for other groups. Similar intercepts (35 dB) among the cross-validation groups indicate that maximum \(Z_H\) at \(-10^\circ\text{C}\) for all 40 storms should decrease to 35 dBZ by the time of cessation (denoted by the black cross in Fig. 4). Since the 40-dBZ echo descends below \(-10^\circ\text{C}\) before the 35-dBZ echo, we will also test the last occurrence of 40 dBZ in an attempt to safely shorten the lightning advisory even more. However, we must be confident that this greater threshold will not prematurely end an advisory and thereby compromise safety.

We also investigated whether any of the base polarimetric products were associated with cessation since they provide important information about hydrometeor size, shape, and orientation that is not given by \(Z_H\) alone. WDSS-II images of these variables offered no obvious visual indication that a storm’s last flash had occurred. Nonetheless, we attempted to quantify these visual observations by employing a statistical approach similar to that described above. Small R values indicated a weak relationship between each polarimetric parameter and time of cessation (Wilks 2011). Since none of the variables converged toward a certain value at the time of cessation, we did not explore them further. Although we did not find these parameters useful when employing a wait-time approach, other approaches might show them to have greater utility as cessation guidance.

To summarize, all four cross-validation groups suggest that descent of 35- and 40-dBZ reflectivity below \(-10^\circ\text{C}\) altitude are the best \(Z_H\) thresholds to examine further. The cross-validation technique also allowed us to test multiple training sets, thereby enhancing confidence that our dependent dataset is sufficient for developing cessation algorithms. Since all 40 storms have a similar intensity (i.e., \(Z_H\)) and decay rate near the time of cessation, the cross-validation training sets will not be used further. Instead, observations and trends will be examined using all 40 isolated storms together.

**b. Using graupel as cessation guidance**

We next investigated whether the presence of graupel in a storm’s convective core is related to lightning cessation. Figure 5 is an example plan view of PID categories at \(-10^\circ\text{C}\) overlaid with flash initiation sources (diamonds).
for a storm at 2213 UTC 30 July 2012. Only flashes within 1 min of the radar time stamp are shown. Almost every flash initiation source is collocated with the presence of graupel at \(-10^\circ C\) (i.e., pink-shaded regions). We observed this relationship for almost all of the storms examined.

Previous studies have shown that the presence of graupel has the greatest correlation with lightning activity of any hydrometeor type, consistent with the NIC mechanism (Deierling et al. 2005; Wiens et al. 2005; Kuhlman et al. 2006; Bruning et al. 2007; Steiger et al. 2007a). In the present study, only graupel exhibited a strong visual relationship with lightning activity. We further investigated the presence of HCA-determined graupel (greatest PID value) by examining the maximum PID value within a \(K\)-means cluster using the \texttt{w2segmotionl} algorithm. It is important to note that the only reason for examining the maximum PID value is because graupel is represented by the greatest PID integer. For example, if hail had been assigned the greatest PID value, one would track graupel’s specific PID value (not the maximum) within a \(K\)-means cluster. Straka et al. (2000) noted that small hail and graupel often coexist and are indistinguishable. Thus, the areas of graupel discussed here also might contain small hail.

Figure 6a shows the distribution of graupel at 1-min intervals from all 40 storms at three temperature altitudes crucial to storm electrification. It indicates all times that graupel was present in the mixed-phase region of a storm’s core before and after cessation. One should note that many of the data points in Figs. 6a and 6b are superimposed on one another, especially near \(t = 0\). The initial loss of graupel in the mixed-phase region at \(-20^\circ C\) occurs \(\sim 10\) min after cessation, followed by a 10–20-min time lag as the storm’s updraft weakens and graupel is present only at lower levels (i.e., \(-10^\circ C\) and \(0^\circ C\)).

Figure 6b shows the last time graupel is present in the core of each storm relative to its time of cessation. The last observation of graupel at \(-20^\circ C\) is more than 15 min before the last flash in 8% of the storms examined. This percentage is greater than observed at \(-10^\circ C\) (0%) and \(0^\circ C\) (0%). Therefore, using the absence of graupel at \(-20^\circ C\) as cessation guidance is not useful since it occurs too far in advance of the last flash, and would produce too many premature advisory cancellations. Conversely, the last observation of graupel at \(0^\circ C\) occurs at least 15 min after the last flash in 48% (19 storms) of the 40 storms. This percentage is greater than observed at \(-10^\circ C\) (25%) and \(\sim 20^\circ C\) (3%). Waiting 15 min after graupel is no longer present at \(0^\circ C\) means that the advisory for 19 of the storms would not end until at least 30 min after the last flash. Thus, using the absence of graupel at \(0^\circ C\)
provides no time savings compared to the 30–30 rule. The last observation of graupel at $-10^\circ$ occurs closer to the time of cessation ($t = 0$; Fig. 6b) than observed at $0^\circ$ or $-20^\circ$. This demonstrates that $-10^\circ$ provides the best combination of time savings without sacrificing safety. The following results will refer only to the $-10^\circ$ level. Although 39 of our 40 storms had HCA-indicated graupel at $-10^\circ$ sometime during their life cycle, one

**FIG. 6.** Temporal distribution of (a) all times and (b) the last time graupel was present in the core of the storm based on tracking all 40 storms at 1-min intervals, where the last flash corresponds to $t = 0$. The different color horizontal groups of symbols represent the three different temperatures crucial to electrification (i.e., $0^\circ$, $-10^\circ$, and $-20^\circ$). Negative times indicate a storm losing graupel at a given temperature level before the last flash, while positive times represent storms that lose graupel after the last flash. No significant regions of graupel were observed in the mixed-phase region of storm cores at times greater than 35 min after cessation.
storm did not (Fig. 6b). This storm seems to be anomalous, attributable to possible errors in the WDSS-II HCA. We hypothesize that some graupel likely was present in the main negative charge region of this storm, but it was not the dominant hydrometeor type within the storm’s convective core according to the fuzzy logic system used in the WDSS-II HCA classification scheme. Another possibility is that the height of the −10°C level in the storm’s environment may be incorrect because of uncertainties in the RAP analyses. The 13-km grid spacing and hourly updates might be too coarse to properly resolve the true altitude of −10°C.

We visually examined plan-view images of the dominant hydrometeor types in our 40 storms at −10°C to observe their evolution relative to lightning cessation. Figure 7 is an example of a typical nonsevere storm on 7 May 2012. Since only flashes within 1 min of each radar time stamp are shown, many flashes are not depicted. The PID categories reveal that ice and snow are the dominant hydrometeors prior to storm formation (Fig. 7a). This is followed by formation of a graupel area (pink area in Fig. 7b) prior to the first flash at 1830 UTC as the storm reaches its mature stage (Fig. 7c). The area of graupel then begins to decrease (Figs. 7d,e) as snow (cyan area) becomes the dominant hydrometeor type after the last flash at 1842 UTC (Fig. 7f).

c. Correlation between graupel and horizontal reflectivity

We next examined how the presence of graupel relates to storm intensity (i.e., $Z_H$). Figure 8 is a plot of graupel and $Z_H$ at −10°C at 1-min intervals from the 40 storms based on the presence or absence of lightning. Lightning events are defined as any 1-min period prior to cessation (i.e., lightning is still occurring). The no lightning events are 1-min periods after cessation. Results indicate that most lightning (72.5%) occurs with the presence of graupel and large $Z_H$ values ($Z_H \geq 35$ dBZ). Conversely, most periods without lightning (55.5%) occur with no graupel and small $Z_H$ values ($Z_H < 35$ dBZ). However, only 37.8% of lightning events contain graupel and exceed the 40-dBZ threshold. This smaller percentage suggests that a threshold of $Z_H \geq 40$ dBZ at −10°C is too lenient to use safely as cessation guidance. Conversely, the combination of graupel and $Z_H \geq 35$ dBZ at −10°C shows promise. We will test these threshold combinations further in section 3e.

d. Single cell on 1 June 2012

Time–height plots were created for each storm to gain insight into their flash characteristics and hydrometeor distributions as the storms neared cessation. Figure 9 describes a storm on 1 June 2012, with Figs. 9b and 9c showing the vertical distribution of hydrometeor type and IC flash initiation sources (white circles). This storm produced no CG flashes, only IC originating above or near the melting level. During the 6–12-min period prior to cessation at $t = 0$, graupel is the dominant hydrometeor type in the layer from 0° to −20°C. This is consistent with the tripole charge structure outlined by Krehbiel (1986) and Williams (2001) in which graupel occurs in the negative charge region (Takahashi et al. 1999; Saunders et al. 2006; Bruning et al. 2010; Akita et al. 2011).

The depth of the graupel layer decreases during the 6-min period prior to the last flash ($t = 0$; Fig. 9b). Thus, we investigated utilizing this decreasing depth as a possible cessation algorithm. That is, waiting 5, 10, or 15 min after the depth of the graupel layer decreases to less than a specified threshold before ending the advisory. We chose to investigate a depth of 2 km so that graupel was required at more than one vertical level of the 1-km WDSS-II data files. That is, we thought cessation would be closely related to a storm’s updraft losing most of its graupel and subsequent NIC, yielding only a thin layer of graupel <2 km. Figure 9b shows that the depth of the graupel layer decreases to less than 2 km at approximately the same time graupel descends below −10°C (~2 min before the last flash). Examination of other storms in our dataset (not shown here) indicated that utilizing graupel depth performs no better as cessation guidance than using the absence of graupel at −10°C. This finding should be tested if a cessation algorithm were being developed for Florida’s cool season or for some other geographic region.

It should be noted that the maximum PID values in Fig. 9b are shown only for tracking graupel in the storm’s core. Thus, Fig. 9b is geared toward graupel dissipation and does not depict a realistic cross section of an actual thunderstorm. Figure 9c shows a better representation of the storm because it depicts a snapshot of merged PID values (w2merger), not just maximum PID values (w2segmotionll).

The maximum flash rate of ~3 flashes min⁻¹ over the entire storm depth (slope in Fig. 9a) is consistent with the findings of Melvin and Fuelberg (2010), suggesting that this cell represents a typical nonsevere storm in the KSC–CCA SF area. There does not appear to be any trend in the cumulative number of flashes or sources (Fig. 9a) during the several minutes prior to cessation.

e. Testing cessation algorithms

Based on the results from sections 3a–c, five parameters show the most promise as cessation guidance and are now examined further. They focus on storm intensity (i.e., $Z_H$) and hydrometeor classification (graupel), each
Fig. 7. Time series of (left) $Z_H$ (color shaded; dBZ) and (right) PID (color coded) of a convective cell at the $-10^\circ\text{C}$ temperature level. The scans are at (a) 1822, (b) 1827, (c) 1829, (d) 1836, (e) 1841, and (f) 1850 UTC 7 May 2012. Yellow diamonds indicate the initiation points for five of the many flashes. The first two occur at 1830 UTC, and the last at 1842 UTC as shown in (c), (e), respectively.
of which is critical to NIC theory. We tested the utility of using the last observation of (algorithm I) \(Z_{H} \geq 40\) dBZ, (algorithm II) \(Z_{H} \geq 35\) dBZ, (algorithm III) graupel, (algorithm IV) graupel and \(Z_{H} \geq 40\) dBZ, and (algorithm V) graupel and \(Z_{H} \geq 35\) dBZ at \(-10^\circ C\) on the independent sample of 10 storms, focusing on whether to use a 5-, 10-, or 15-min wait time before ending the advisory. This provided 15 cessation algorithms (five criteria at three wait times).

It should be noted that one of the storms in the independent dataset exhibits a maximum interval between flashes greater than 20 min, and one exhibits an apparent cessation longer than 30 min but then unexpectedly produces an additional flash. Thus, even waiting 30 min after no lightning is detected (the 30–30 rule) does not guarantee that a storm will not produce another flash. One can only guarantee no premature advisory cancellations by never ending the advisories—a useless approach. Waiting too long to end the advisory would not only curtail outdoor activities, but still would not ensure that personnel and facilities are safe. Therefore, our cessation algorithms seek to balance safety and time savings.

Statistical metrics describe the performance of each of the 15 algorithms, including probability of detection (POD), success ratio (SR), and critical success index (CSI). These statistics are based on applying the algorithms to the independent sample of 10 storms. Future research should evaluate the algorithms on a much larger independent dataset to increase confidence and reliability with them. The \(2 \times 2\) contingency table (Table 2) shows how each event was classified. A hit occurs when an algorithm ends the lightning advisory (based on threshold and wait time) after the last flash. Conversely, a false alarm occurs anytime an algorithm ends the advisory prematurely (i.e., before the last flash has occurred). This is an especially dangerous situation. A missed event is identified when the storm never meets the threshold of our cessation algorithm and, therefore, the advisory is never ended. Finally, we did not include predicted null events because we only consider electrified storms, in which cessation must occur. Therefore, our skill scores are not inflated by a large number of nonevents.

The SR is a derived skill score (SR = 1 − false alarm ratio). SR is the most crucial metric for testing cessation algorithms. Although we desire algorithms with a large POD, it is unrealistic to expect to correctly end every advisory. However, we do want to be highly confident that there will be no additional flashes after advisories are ended since false alarms can be deadly. Thus, a large SR is desired. A missed event does not injure anyone, but too many of them will hinder the effectiveness of an algorithm. Thus, CSI also is important since it considers both false alarms and misses.

We examined the performance of the potential cessation algorithms on all 10 storms. The statistics for each algorithm are given in Table 3, while Fig. 10 is a performance diagram (Roebber 2009) that simultaneously depicts the success metrics (SR, POD, CSI, and bias). Bias is defined as the ratio of POD to SR. Useless cessation algorithms will exhibit an SR, POD, CSI, and bias that approach unity (top right; Fig. 10). Results show that the majority of the algorithms with relatively poor skill scores utilized a 5-min wait time (red symbols). This short wait time provides little confidence to forecasters since the storm could just be weakening temporarily. A longer wait time provides more confidence that the storm has lost most of its charge.

Four of the algorithms in Fig. 10 stand out from the rest: III, which features the last occurrence of graupel at \(-10^\circ C\) using 10- and 15-min wait times (green and blue circles, respectively), and V, which includes the combination of graupel and \(Z_{H} \geq 35\) dBZ at \(-10^\circ C\) using 10- and 15-min wait times (open green and blue triangles, respectively). All four yield perfect SR and CSI results of 1.0 (Fig. 10). These four algorithms utilize HCA-determined graupel, strongly linking them to NIC theory.

Wait times longer than 15 min also were examined for the reflectivity-based algorithms (I and II) since their skill scores could be improved. Increasing the wait period from 15 to 20 min improved SR and CSI scores from 0.9 to 1.0 when utilizing algorithm II (\(Z_{H} \geq 35\) dBZ at

![Figure 8](image)
However, this longer wait period provides minimal time savings compared to the 30–30 rule, ending an advisory an average of 23.1 min after the last flash. Furthermore, algorithm I ($Z_{H} = 40$ dBZ at $-10^\circ$C) still performs poorly using a 20-min wait time, ending only 6 of the 10 advisories safely.

**f. Time savings compared to the 30–30 rule**

Table 4 contains statistics for the 15 potential cessation algorithms applied to all 10 independent storms. We focus on the four best-performing algorithms (III and V) to determine which provides the optimal combination of safety and time savings. Since none of the algorithms prematurely ends the advisory for any of the 10 storms, the two algorithms using a 10-min wait time save the most time (Table 4). Beyond this wait period, there is no improvement in skill scores of the graupel-based algorithms.

Implementing a 10-min wait time using algorithms III and V safely ends the advisory an average of 16.8 and
17.9 min after the last flash, respectively (boldface; Table 4). Since they both exhibit similar skill scores (Table 3; Fig. 10) and time savings (Table 4), we suggest utilizing algorithm V, the combination of graupel and $Z_H \geq 35 \text{ dBZ}$ at $-10^\circ\text{C}$ with a 10-min wait period. This approach uses two parameters (HCA-determined graupel and $Z_H$), providing greater confidence than using PID classification alone.

Proposed algorithm V improves on the 30–30 rule and the 45WS’s most conservative wait time by 12.1 min (Table 4). Figure 11 further examines the performance of this algorithm compared to the presently used 30–30 rule. The algorithm 1) saves time, safely ending the advisory for nine storms; 2) does not save time but still safely ends the advisory for one storm; and, most importantly, 3) does not prematurely end the advisory for any of the 10 storms examined. Based on these 10 storms, the safety of our proposed algorithm surpasses that of the 30–30 rule, which ends one advisory prematurely. However, it should be emphasized that this 10-min wait period should be considered tentative. As evidence, two storms in the dependent sample (Fig. 6b) lose graupel at $-10^\circ\text{C}$ more than 10 min before the last flash. Utilizing our proposed algorithm V with a 10-min wait period would end the lightning advisory before the last flash for these two storms. Thus, a much larger sample size of independent storms and more research are needed to increase confidence in our findings.

4. Implications for the 30 nonisolated cells

The nonisolated storms were problematic for creating cessation guidance. Lightning channels initiated in nearby electrically active storms either traversed or came very near 30 of our dissipating study cells at least once during their lifetime. In some cases, these channels got so close to the study cell that an observer on the ground might conclude that the flash was initiated by the study cell itself.

None of the 30 storms was totally isolated but did fit the following criteria: 1) the cell was embedded in stratiform cloud (composite $Z_H \geq 15 \text{ dBZ}$), 2) there was continuous stratiform cloud between the embedded cell and the nearby electrically active storm (the flash did not pass through clear air), 3) the active storm was within $\sim 50$ km of the embedded cell, and 4) the active storm still had graupel in its core at $-10^\circ\text{C}$. In many cases, lightning from more than one electrically active storm interacted with the dissipating study cell.

As an example, the focus cell in Fig. 12 is marked by the blue-dashed outline. Figure 12a (right) shows that the cell still has graupel at $-10^\circ\text{C}$ and, therefore, probably can initiate lightning on its own. However, a lightning channel initiated in the nearby MCS propagates westward $\sim 10$ km through stratiform cloud before traversing the study cell at 2227 UTC. This flash is not especially dangerous since the study cell’s core still contains graupel at $-10^\circ\text{C}$ and is initiating lightning. Thus, if the previously derived cessation algorithm were being used, it would not have ended the advisory.

Figure 12b ($\sim 30$ min later at 2257 UTC) shows the same, now virtually dissipated cell (blue-dashed outline), but $\sim 20$ min after it last contained graupel at $-10^\circ\text{C}$. Based on results from Lund et al. (2009), we hypothesize that the decaying cell would not have had sufficient charge on its own to support additional flashes since NIC probably had ceased. However, a final flash initiates in the nearby active storm, propagates through $\sim 17$ km of stratiform cloud with composite $Z_H \geq 15 \text{ dBZ}$, and traverses the dissipated cell. We hypothesize that this flash probably would not have occurred if the cell had been buffered from the MCS farther east by a region of $Z_H < 15 \text{ dBZ}$. The applicability of using $Z_H = 15 \text{ dBZ}$ as the threshold requires additional study, especially in different seasons and different geographic regions.

The early sign of lightning traversing our cell (Fig. 12a) is important because it seems to be a predictor
of future behavior. In other words, lightning that extends outside of a nearby storm into stratiform cloud should alert a forecaster that the stratiform region might be sufficiently charged to facilitate further channel propagation toward the focus cell regardless of whether that cell has graupel at $-10^\circ$C.

Figure 13 depicts a different scenario that is equally dangerous. Lightning is initiated in electrically active storm A (Fig. 13a), and traverses eastward $\sim30$ km of stratiform cloud before ending very near ($\sim5$ km) the study cell (blue-dashed outline) at 2255 UTC. This time marks the last observation of graupel at $-10^\circ$C in the cell. Thus, this cell was not expected to initiate additional lightning on its own since there probably was little or no charging occurring at the time. However, $\sim23$ min later (Fig. 13b), a lightning channel from storm A and another from an MCS farther east extend through the stratiform region in which our study cell is embedded and end $\sim18$ km from the cell. Even though this distance from our study cell is greater than in the earlier example, this scenario is still dangerous because the stratiform region continues to facilitate channel propagation (Dye and Willett 2007; Dye et al. 2007).

Overall, three different scenarios were observed among the 30 embedded cells:
1) lightning initiated by a nearby active storm traveled through stratiform cloud with composite $Z_H \geq 15$ dBZ and traversed the study cell (Fig. 12),
2) lightning initiated by a nearby active storm traversed stratiform cloud and ended very near (e.g., $<$10 km) the study cell (Fig. 13a), or
3) lightning initiated in a nearby active storm traveled through stratiform cloud but remained farther (e.g., $>10$ km) from our study cell (Fig. 13b).

More than one of these scenarios often was observed with a single dissipating cell. Thus, the threat of lightning near the study cell has not ended as long as a nearby
active storm still has graupel and is producing lightning, and an electrically charged stratiform region connects the two storms. The specific path that a lightning channel follows within the stratiform region likely involves complex charge structures that are beyond the scope of this study (Weiss et al. 2012).

Lightning channels through stratiform regions are dangerous because they can produce CG strikes anywhere along their path. Rutledge and Petersen (1994) observed CG flashes in stratiform regions of MCS clusters having \(Z_H \geq 15\) dBZ in their mixed-phase regions. Several studies have attributed the electrification of stratiform regions to the advection of charge from the parent convective core (Orville et al. 1988; Rutledge and MacGorman 1988). Recent research has shown that charge and subsequent lightning also can be generated locally in the stratiform region itself (Schuur and Rutledge 2000; Lang et al. 2004b; Lang and Rutledge 2008; Weiss et al. 2012). Thus, an electrically charged stratiform region might on its own initiate a lightning channel that jeopardizes safety near a decaying cell.

Each of the 30 embedded nonisolated cells mentioned above was within \(\sim 50\) km of a storm that was still producing lightning. Although we observed no flashes longer than \(\sim 50\) km across broad stratiform areas, previous studies have observed even longer flashes (Lyons et al. 2003; Kuhlman et al. 2009). Determining the maximum horizontal distance that lightning channels can traverse stratiform areas should be studied further. Determining the probability of a lightning channel extending a certain distance (i.e., 30, 40, or 50 km) also should be done.

Prior to cessation, a majority of the 30 embedded cells exhibited a deep layer of graupel (not shown here) in and slightly below the layer between \(-10^\circ\) and \(-20^\circ\), similar to that observed in Fig. 9. However, once graupel was no longer present in the layer, we observed nothing unique in the structure of the cell or its vertical distribution of hydrometeors. There was no indication that it would later have an unexpected last flash other than its close proximity to a nearby active storm. Thus, these results suggest that an area of \(Z_H < 15\) dBZ may limit or even prohibit channel propagation. Steiger et al. (2007b) found diminished lightning activity in areas of mean \(Z_H\) between 10 and 20 dBZ, and increased lightning activity in a “bridge” of enhanced \(Z_H\) values connecting the convective and stratiform regions (McCormick 2003). The future studies that are needed to confirm our hypothesis should examine the relationship between areas of \(Z_H < 15\) dBZ (or some other appropriate threshold) and the probability of a lightning channel traversing that area.

The 30 embedded nonisolated cells were the only types of storms to violate our best cessation algorithm from section 3 (combination of graupel and \(Z_H \geq 35\) dBZ at \(-10^\circ\)C using a 10-min wait period). If our proposed algorithm had been used on the 30 cells, it would have safely ended the advisory in 13 of the 30 cases, produced three misses, and prematurely ended the advisory for 14 cells. This finding is consistent with

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### Table 4. Analysis of time savings for the five potential cessation algorithms at three different wait times tested on the 10 independent storms.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Wait time (min)</th>
<th>Avg time (min)</th>
<th>Max time (min)</th>
<th>Std dev (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: (Z_H \geq 40) dBZ</td>
<td>5</td>
<td>7.7</td>
<td>14.0</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>12.7</td>
<td>19.0</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>17.7</td>
<td>30.5</td>
<td>10.6</td>
</tr>
<tr>
<td>II: (Z_H \geq 35) dBZ</td>
<td>5</td>
<td>11.0</td>
<td>21.6</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15.3</td>
<td>26.6</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>20.3</td>
<td>31.6</td>
<td>9.1</td>
</tr>
<tr>
<td>III: graupel</td>
<td>5</td>
<td>13.6</td>
<td>26.0</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>16.8</td>
<td>31.0</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>23.2</td>
<td>36.0</td>
<td>10.7</td>
</tr>
<tr>
<td>IV: graupel and (Z_H \geq 40) dBZ</td>
<td>5</td>
<td>17.0</td>
<td>26.0</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>18.9</td>
<td>31.0</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>23.9</td>
<td>36.0</td>
<td>12.5</td>
</tr>
<tr>
<td>V: graupel and (Z_H \geq 35) dBZ</td>
<td>5</td>
<td>13.7</td>
<td>26.0</td>
<td>9.9</td>
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<tr>
<td></td>
<td>10</td>
<td>17.9</td>
<td>31.0</td>
<td>10.7</td>
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<tr>
<td></td>
<td>15</td>
<td>24.3</td>
<td>36.0</td>
<td>10.1</td>
</tr>
</tbody>
</table>
that of Fehr et al. (2005), who found a poor correlation between lightning and graupel mass in an MCS because of electrical interactions between cells. Thus, we do not recommend that any forecaster use our proposed algorithm as cessation guidance for nonisolated storms.

5. Summary and conclusions

This study was motivated by the 45WS’s need to improve guidance of lightning cessation near the KSC–CCAFS area. Based on observations from 40 isolated storms, three radar parameters applied at \(-10^\circ\)C were found to exhibit the greatest potential for indicating cessation, 1) \(Z_H\), 2) graupel, and 3) graupel and \(Z_H\). We tested thresholds of these parameters using three different wait times (5, 10, and 15 min). This produced 15 cessation algorithms to test on 10 independent storms. The results show the importance and utility of using graupel to improve cessation guidance for storms near KSC–CCAFS.

Based on the independent storms tested, we suggest using an algorithm that utilizes the presence of graupel and \(Z_H \geq 35\) dBZ at \(-10^\circ\)C. One waits 10 min after these thresholds are no longer met before ending the lightning advisory. The combination of HCA-determined graupel and \(Z_H\) performed better than \(Z_H\) alone. The proposed algorithm was the safest of those tested based on SR and CSI scores. It safely ended the advisory for all 10 independent storms after the last flash. The advisories for 9 of the 10 storms were ended earlier than the 30–30 rule. Thus, the proposed algorithm also saves time (12.1-min average) compared to the 30–30 rule and the 45WS’s most conservative wait time.

We must emphasize that although a 10-min wait period performed best on the 10 independent storms in the current study, this wait time must be tested further. A longer
wait time might be necessary for different modes of convection or in different geographic regions and seasons.

Lund et al. (2009) found that storms can initiate flashes after NIC has stopped, utilizing their previously generated charge. Thus, our proposed wait time of 10 min suggests that an isolated storm will not initiate flashes beginning 10 min after NIC is assumed to have stopped contributing additional charging. However, this does not consider processes other than NIC, such as convergence or transport of charge, which could also contribute to the charging of a storm (Kuhlman et al. 2009; Weiss et al. 2012).

Examination of the 30 nonisolated, dissipating cells showed the importance of lightning in a nearby storm and the presence of stratiform cloud connecting a decaying storm to an active storm. No algorithm that we developed safely ended advisories for the 30 cells embedded within stratiform clouds. Only storms that had an area of composite $Z_H < 15 \text{ dBZ}$ separating them from nearby thunderstorms had their advisories safely ended. Thus, the more isolated a dissipating storm is, the more likely it is that the proposed algorithm will be successful. For a less isolated cell, we suggest waiting until all active storms connected to it by stratiform clouds no longer contain graupel and $Z_H \geq 35 \text{ dBZ}$ at $-10^\circ\text{C}$ for at least 10 min before ending the advisory. In other words, one must monitor cessation for neighboring storms in addition to the focus storm since only examining the focus storm may give a false sense of security to people in the area.

A much larger sample size (e.g., 1000 storms) is needed to provide greater confidence in the proposed algorithm for central Florida. Multicell, quasi-linear storms, severe storms, and storms occurring during Florida’s cool season also require further study. Previous research has noted differences in lightning characteristics between geographic regions (e.g., MacGorman et al. 2011). Thus, different geographic locations having total lightning networks, such as those in Oklahoma, Texas, northern Alabama, and the Washington, D.C., area...
should be considered. The thresholds and wait times of this study probably will need to be modified in these other regions. Finally, future studies should address the electrical structure of stratiform regions to understand better their ability to initiate or propagate lightning channels.

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