Kinematic and Microphysical Significance of Lightning Jumps versus Nonjump Increases in Total Flash Rate

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Abstract

Thirty-nine thunderstorms are examined using multiple-Doppler, polarimetric, and total lightning observations to understand the role of mixed-phase kinematics and microphysics in the development of lightning jumps. This sample size is larger than those of previous studies on this topic. The principal result of this study is that lightning jumps are a result of mixed-phase updraft intensification. Larger increases in intense updraft volume ($\geq 10 \text{ m s}^{-1}$) and larger changes in peak updraft speed are observed prior to lightning jump occurrence when compared to other nonjump increases in total flash rate. Wilcoxon–Mann–Whitney rank sum testing yields $p$ values $\leq 0.05$, indicating statistical independence between lightning jump and nonjump distributions for these two parameters. Similar changes in mixed-phase graupel mass magnitude are observed prior to lightning jumps and nonjump increases in total flash rate. The $p$ value for the graupel mass change is $p = 0.096$, so jump and nonjump distributions for the graupel mass change are not found to be statistically independent using the $p > 0.05$ significance level. The timing of updraft volume, speed, and graupel mass increases is found to be 4–13 min in advance of lightning jump occurrence. Also, severe storms without lightning jumps lack robust mixed-phase updrafts, demonstrating that mixed-phase updrafts are not always a requirement for severe weather occurrence. Therefore, the results of this study show that lightning jump occurrences are coincident with larger increases in intense mixed-phase updraft volume and peak updraft speed than smaller nonjump increases in total flash rate.

1. Introduction

Sudden increases in total flash rates are denoted as lightning jumps. Research into lightning jumps has primarily focused on the correlation between lightning jumps and severe weather$^1$ occurrence (e.g., Williams et al. 1999; Schultz et al. 2009; Gatlin and Goodman 2010; Schultz et al. 2011; Rudlosky and Fuelberg 2013). However, these studies lack analysis of the microphysical and dynamical mechanisms that lead to a rapid increase in total flash rate.

Several studies observed good correlation between total lightning trends and mixed-phase ice mass or updraft volume, but poorer correlation between total lightning and maximum updraft speed over the entire life cycle of thunderstorms (e.g., Workman and Reynolds 1949; Goodman et al. 1988; Tuttle et al. 1989; Dye et al. 1989; Carey and Rutledge 1996; Lang and Rutledge 2002; Wiens et al. 2005; Tessendorf et al. 2005; Kuhlman et al. 2006; Deierling et al. 2008; Deierling and Petersen 2008).

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$^1$ Defined as the presence of hail $\geq 2.54 \text{ cm}$, winds $\geq 26 \text{ m s}^{-1}$, or a tornado.

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These studies relied on the observed connection between kinematics, microphysics, and electrification within thunderstorms via the noninductive charging mechanism (e.g., Takahashi 1978; Saunders et al. 2006).

Electrification within thunderstorms is found to occur on the order of the quarter- to half-life of an ordinary thunderstorm.\(^2\) Research shows that initial electrification in the primary development of thunderstorms is approximately 10–15 min (e.g., Dye et al. 1986; Bringi et al. 1997). Lightning jumps themselves also occur on time scales that are on the order of several minutes (Goodman et al. 1988; Williams et al. 1989, 1999). Therefore, storm properties that are well correlated to total flash rate on longer time scales may not represent the same mechanisms that result in lightning jumps.

Schultz et al. (2015) examined the correspondence between lightning jumps and trends in mixed-phase graupel mass, maximum updraft speed, and updraft volume on 15-min time scales for four thunderstorms of varying morphology. These specific parameters were chosen because of their strong correlations to total flash rate from studies mentioned previously in this paper. Schultz et al. (2015) showed that lightning jumps occur when the 10 m s\(^{-1}\) updraft volume and mixed-phase graupel mass increase prior to jump occurrence. They also determined that maximum updraft speed increases in 8 of the 12 flash rate periods examined. However, Schultz et al. (2015) did not robustly demonstrate how the kinematic and microphysical mechanisms examined differ between lightning jumps and other nonjump increases in total flash rate because of a small sample size.

Therefore, the goal of this research is to determine whether there are statistically significant differences between lightning jumps and nonjump increases in total flash rate using a large sample of thunderstorm observations. Analysis of the kinematic and microphysical characteristics will assess if larger changes in the magnitude of mixed-phase graupel mass, updraft volume, or maximum updraft speed occur prior to lightning jumps versus other nonjump increases in total flash rate because of a small sample size.

Therefore, the goal of this research is to determine whether there are statistically significant differences between lightning jumps and nonjump increases in total flash rate using a large sample of thunderstorm observations. Analysis of the kinematic and microphysical characteristics will assess if larger changes in the magnitude of mixed-phase graupel mass, updraft volume, or maximum updraft speed occur prior to lightning jumps versus other nonjump increases in total flash rate. This analysis will also evaluate the temporal correspondence between the 2σ lightning jump algorithm (Schultz et al. 2009, 2011, 2015) and the underlying kinematic and microphysical thunderstorm characteristics needed for rapid electrification. The 2σ algorithm is currently being used experimentally at the National Oceanic and Atmospheric Administration’s Hazardous Weather Testbed (NOAA HWT; Calhoun 2015) in preparation of the launch of GOES-R’s Geostationary Lightning Mapper (GLM; Goodman et al. 2013).

### 2. Data and methods

The data, study domain,\(^3\) and analysis methods are similar to those of Schultz et al. (2015) for continuity between the results of that study and the present study. The focus is on using total lightning, polarimetric and multi-Doppler data, and analysis to characterize kinematic and microphysical changes within a thunderstorm prior to any increase in total flash rate. This research provides more comprehensive statistical metrics related to the physical mechanisms hypothesized to modulate electrification and lightning production within thunderstorms.

A total of 39 thunderstorms are used in this analysis. The convective intensity of the thunderstorms examined ranges from weak ordinary multicellular convection and low-topped winter convection to bowing segments within quasi-linear convective systems (QLCSs) and supercells (Table 1). Of the 39 thunderstorms, 20 thunderstorms contain at least one lightning jump, and 19 possess zero lightning jumps while they are within the multi-Doppler domain. Twenty-three of the 39 thunderstorms are multicellular thunderstorms, 10 thunderstorms are supercells, 3 are low-topped supercell storms, 2 are bowing segments within QLCSs, and 1 storm is in the outer bands of a remnant tropical cyclone. In total,

\(^2\) The duration of an ordinary thunderstorm is 30–60 min (Byers and Braham 1949).

\(^3\) See Fig. 1 in Schultz et al. (2015).
214 analysis periods of 15 min prior to an increase in total flash rate (both jumps and nonjump increases) are analyzed from these 39 thunderstorms. Properties that are examined in this analysis include mixed-phase graupel mass (from $-10^\circ$ to $-40^\circ$C), 5 and 10 m s$^{-1}$ mixed-phase updraft volumes, and maximum updraft speed.

\textbf{a. Radar data}

The same radar data and methodologies used in Schultz et al. (2015) are employed in this study. The University of Alabama in Huntsville’s (UAH) Advanced Radar for Operational Research (ARMOR; Schultz et al. 2012; Knupp et al. 2014) and the National Weather Service’s (NWS) radar located at Hytop, Alabama (KHTX; Crum and Alberty 1993), are used for three-dimensional retrieval of velocity and bulk characterization of hydrometeor types within thunderstorms. ARMOR can be taken out of its default five-tilt operational mode to collect higher temporal resolution and larger volumetric data for research purposes. All radar data are corrected for attenuation and differential attenuation (Bringi et al. 2001). Aliased velocities are unfolded using National Center for Atmospheric Research’s (NCAR) SOLO software (Oye et al. 1995) and ground clutter, sidelobe, and second-trip echoes are also removed from all radar data. Data are gridded to a Cartesian coordinate system using a grid spacing of $1\text{ km} \times 1\text{ km} \times 1\text{ km}$ on a grid of $300\text{ km} \times 300\text{ km} \times 19\text{ km}$. This spacing is chosen because of the resolution limitations of the longer baseline used for the ARMOR KHTX domain (e.g., Davies-Jones 1979; Deierling and Petersen 2008). A Cressman weighting scheme is implemented using a 1-km radius of influence centered at each grid point with NCAR’s REORDER software (Oye and Case 1995). Individual thunderstorms are identified and semiobjectively tracked using the Thunderstorm Identification Tracking Analysis and Now-casting (TITAN; Dixon and Wiener 1993) algorithm to assign radar and lightning characteristics to individual storms. This tracking method is the same as has been used in previous lightning jump studies (Schultz et al. 2009, 2011, 2015).

The NCAR’s Custom Editing and Display of Reduced Information in Cartesian Space (CEDRIC; Mohr et al. 1986) is used to perform multi-Doppler synthesis. Vertical velocity retrievals are calculated using radial velocity measurements from two or more radars and a reflectivity-based hydrometeor fall speed relationship to solve a set of linear equations (e.g., Armijo 1969; O’Brien 1970; Brandes 1977; Ray et al. 1980; Deierling and Petersen 2008; Schultz et al. 2015). Horizontal velocity components $u$ and $v$ are derived from radial velocity measurements from both radars and are used to solve for the vertical velocity component $w$ by integrating the anelastic continuity equation.

Similar to Schultz et al. (2015), the variational integration technique is utilized in this study to evaluate trends in updrafts within thunderstorms (e.g., O’Brien 1970; Matejka and Bartels 1998, their section 2e). The variational technique is chosen for this analysis for continuity between the methods used in this study and other studies using the ARMOR KHTX baseline (e.g., Deierling and Petersen 2008; Johnson 2009; Mecikalski et al. 2015; Carey et al. 2016). The advantage of the variational integration technique is that it redistributes errors from both boundary conditions to produce profiles of vertical air motion and divergence that converge to a solution (O’Brien 1970; Matejka and Bartels 1998).

The downward integration scheme could also be utilized for similar analysis of updrafts.

Vertical velocity is set at 0 m s$^{-1}$ at the upper and lower bounds of integration (0 and 17 km). Integration of the anelastic mass continuity equation is performed from the upper and lower bounds of integration for all points within the multi-Doppler domain. Upward integration is performed from 0 up to 3 km and downward integration is performed from the upper boundary from 17 km down to (and including) 3 km. Upward integration is only used below 3 km because of potential errors introduced into the calculation of divergence and vertical velocity at low levels from radar beam height limitations (i.e., radar data do not extend all of the way to the surface). However, updraft information used for analysis is limited to from $-10^\circ$ to $-40^\circ$C, which is $\geq4$ km in the 39 cases examined, and these levels utilize calculations from the downward integration of continuity. Integration of the anelastic continuity equation results in an estimate of vertical velocity for each 1-km$^2$ volume where $u$, $v$, and the divergence are calculated in the vertical column.

Analysis of updraft speed and volume are limited to the mixed-phase region of the thunderstorm (i.e., between the $-10^\circ$ and $-40^\circ$C isotherms) because the mixed-phase region is where charge development and separation take place and ultimately lead to electrical breakdown (e.g., Dye et al. 1986; Carey and Rutledge 1996; Bringi et al. 1997; Deierling and Petersen 2008; Calhoun et al. 2013). Maximum updraft speed and a sum of 1-km$^2$ updraft volumes with speeds $\geq 5$ and 10 m s$^{-1}$ are computed from the multi-Doppler Cartesian grids for all multi-Doppler syntheses in which a thunderstorm is identified and tracked by TITAN. The longer baseline between the radars means that updraft values calculated in the study are smaller in magnitude than the true updraft observed if higher-resolution observations were available. However, the trend in the updraft can still be
characterized, especially with horizontal resolution \( \leq 1.5 \text{ km} \) in the domain used in this study. This longer baseline approach is used in similar lightning/updraft studies like Deierling and Petersen (2008), Mecikalski et al. (2015), and Carey et al. (2016).

Particle identification is performed using ARMOR radar data and the NCAR Particle Identification Algorithm (PID; Vivekanandan et al. 1999) modified for C-band observations (Deierling et al. 2008; Johnson 2009; Schultz et al. 2015) to identify the dominant scatterer observed in each ARMOR radar volume. The graupel/small hail category is the primary hydrometeor of interest in this study because of graupel’s strong tie to electrification and lightning production in thunderstorms through noninductive charge (NIC) processes (e.g., Carey and Rutledge 1996; Saunders et al. 2006; Deierling et al. 2008). Graupel mass is calculated using a \( z-M \) relationship of

\[
\text{mass} \left( \text{g m}^{-3} \right) = 0.0052 \times z^{0.5},
\]

from Heymsfield and Miller (1988). The letter \( z \) represents the reflectivity factor (in linear units of \( \text{mm}^6 \text{m}^{-3} \)), and this calculation is made for each volume where graupel/small hail is identified to be the dominant particle in a 1-km\(^3\) volume. All 1-km\(^3\) hydrometeors between \(-10^\circ\) and \(-40^\circ\) C that also fell inside the thunderstorm’s TITAN footprint are then used to calculate a total mass for the storm at each ARMOR radar volume time.

### b. Lightning data

The same lightning data and methods used in Schultz et al. (2015) are employed in this study. Total lightning information is collected by the North Alabama Lightning Mapping Array (NALMA; Koshak et al. 2004; Goodman et al. 2005). Very high frequency (VHF) source points are combined into corresponding flashes using a flash-clustering algorithm developed by McCaul et al. (2009). This clustering algorithm requires that all VHF source points 0.3 s apart in time and that satisfy an azimuth and range-dependent spatial separation restriction be grouped into a single lightning flash.\(^4\) A flash must have a minimum of 10 VHF source points to be considered in this analysis.

**The Lightning Jump**

The sigma-level configuration of the 2\(\sigma\) lightning jump algorithm is used to categorize jump and nonjump increases in total flash rate within this study (Schultz et al. 2009, 2011). Sigma level is represented by

\[
\text{sigma level} = \frac{\text{DFRDT}_{t_6}}{\sigma(\text{DFRDT}_{t_1-2, t_4-6, t_8-10})},
\]

where DFRDT\(_{t_6}\) represents the time rate of change of the total flash rate at the current time and \(\sigma(\text{DFRDT}_{t_1-2, t_4-6, t_8-10})\) represents the standard deviation of the time rate of change for the previous 12 min of lightning data starting at \( t - 2 \). Please see the appendix or Schultz et al. (2011), Chronis et al. (2015), and Schultz et al. (2015) for more details on the calculation of the 2\(\sigma\) lightning jump algorithm. All increases in total flash rate (i.e., positive sigma level) are examined, and flash rate increases are binned into two groups by their sigma level. A nonjump increase in flash rate has a sigma level \(< 2\) (hereafter defined as the 0–2 category) and a lightning jump has a sigma level \(\geq 2\) (hereafter defined as the 2+ category).

### c. Analysis windows

Trends in updraft speed, updraft volume, and graupel mass are determined in the following manner. First, the time of the flash rate increase \( t_6 \) is used to identify radar volumes within \( \pm 2 \text{ min} \) of occurrence. If two radar volumes are available, the one closest to the time of the flash rate increase is used. Similarly, the closest radar volume to the time 15 min prior to the flash rate increase (i.e., \( t - 15 \)) is also identified. This radar volume also must occur within \( \pm 2 \text{ min} \) of the \( t - 15 \) time. Next, the local trend in each radar-derived parameter is determined by subtracting the value at time \( t - 15 \) from time \( t_6 \). The magnitude of the change is placed into the corresponding sigma-level category. A 15-min analysis window is chosen because it is on the order of the quarter- to half-life of an ordinary thunderstorm (Byers and Braham 1949); it is the approximate amount of time for the onset of electrification (Dye et al. 1986; Bringi et al. 1997), and this period allows for two to three radar updates from the WSR-88D radars to obtain trends in other intensity metrics like maximum expected size of hail (MESH; Witt et al. 1998) or azimuthal shear. Lengthening the analysis window could also incorporate data that are less likely to be attributed to the development of a lightning jump (Schultz et al. 2015).

### d. Statistical significance

Assessment of statistical independence between the jump and nonjump distributions is made for each kinematic or microphysical quantity in this study (i.e., mixed-phase updraft volume, updraft speed, or graupel mass). A Wilcoxon–Mann–Whitney rank sum test is used to determine the degree of independence between the 0–2

\(^4\) For more information on the spatial requirements, see McCaul et al. (2009) and references therein.
and 2+ sigma-level data distributions for updraft volume, updraft speed, and graupel mass (Wilks 1995, 159–163). The use of the rank sum test is ideal for this dataset because the sampling distribution of the data is unknown, and this test is resistant to any potential outliers. The $Z$ scores and $p$ values for each of the comparisons are presented to illustrate the level of significance between the 0–2 and 2+ sigma-level categories. The null hypothesis is that the 0–2 and 2+ sigma-level are drawn from the same distribution for each parameter examined in this study. Thus, if the $p$ value is $p \leq 0.05$, the null hypothesis is rejected, and the property is more likely observed with lightning jump occurrence than a general increase in flash rate. If the $p$ value is $p > 0.05$, the null hypothesis is supported, and the kinematic/microphysical property is observed for any increase in total flash rate and not solely for lightning jumps.

### 3. Results

Parameters of mixed-phase graupel mass, updraft volume, and updraft speed are examined to determine differences in the kinematic and microphysical growth within a thunderstorm prior to lightning jumps and nonjump increases in total flash rate. Changes in these quantities in a 15-min analysis window will help determine the degree to which well-correlated parameters observed in previous studies can differentiate between lightning jumps and nonjump increases in the total flash rate. Ultimately, lightning jumps could be used to infer a higher likelihood that a specific physical process is present if a lightning jump is observed, especially for physical parameters that are not readily available (e.g., updraft speed, updraft volume).

#### a. Mixed-phase graupel mass

Growth of mixed-phase graupel mass in this sample of thunderstorms is observed prior to the majority of the total flash rate increases (Fig. 1). The median changes for the 0–2 and 2+ sigma-level categories are 5.70 and $7.15 \times 10^7$ kg, respectively. There is considerable overlap of the inner quartile ranges (IQRs) within each sigma-level category. Wilcoxon–Mann–Whitney rank sum testing illustrates that the two distributions are statistically similar (Table 2). The 0–2 and 2+ graupel mass distributions result in a $Z$ score of 1.065, with a one-tailed $p$ value of 0.096. This $p$ value is larger than the $p = 0.05$ value used to determine statistical independence, so the null hypothesis of similar distributions is supported.

![Fig. 1. Box plots of storm graupel mass change (kg) vs the sigma level of the subsequent increase in total flash rate. Data from nonjump increases in total flash rates are in blue (i.e., 0–2 sigma level), while data from lightning jump events are in orange. Median, 25th, and 75th changes are to the right of each box, and the population size of each bin is on the left. The exes (X) indicate the individual data points within each sigma-level category.](image)

#### Table 2. The $Z$ scores and $p$ values using Wilcoxon–Mann–Whitney rank sum testing between the 0–2 and 2+ sigma-level categories for graupel mass change (kg), 5 and 10 m s$^{-1}$ updraft volume change (km$^3$), and maximum vertical velocity (VV) change (m s$^{-1}$).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0–2 Sigma Level</th>
<th>2+ Sigma Level</th>
<th>MaxVV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Graupel Mass</strong></td>
<td>1.065</td>
<td>3.286</td>
<td></td>
</tr>
<tr>
<td><strong>5 m s$^{-1}$</strong></td>
<td>1.323</td>
<td>1.987</td>
<td>5.0 $\times$ 10$^{-4}$</td>
</tr>
<tr>
<td><strong>10 m s$^{-1}$</strong></td>
<td>0.933</td>
<td>0.0234</td>
<td></td>
</tr>
<tr>
<td><strong>MaxVV</strong></td>
<td>5.0 $\times$ 10$^{-4}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
and larger increases in mixed-phases graupel mass are not observed to statistically discriminate between lightning jump and nonjump increases in total flash rate.5

b. Updraft volume

The change in mixed phase 5 m s\(^{-1}\) updraft volume also does not discriminate between lightning jump and nonjump increases in total flash rate. Small differences are observed in the distributions between the two sigma-level categories (Fig. 2a). Medians of the 0–2 and 2+ sigma-level categories are 66 and 125 km\(^3\), respectively. Wilcoxon–Mann–Whitney rank sum testing shows that these two distributions are statistically similar Fig. 2a. The Z score and p value of 1.323 and 0.093 for 5 m s\(^{-1}\) updraft volume change supports the null hypothesis since the p value is larger than the \(p = 0.05\) independence threshold. This result demonstrates that larger increases in 5 m s\(^{-1}\) updraft volume are not observed to statistically discriminate between lightning jumps and nonjump increases in total flash rate.

The change in mixed-phase 10 m s\(^{-1}\) updraft volume prior to flash rate increases shows larger differences

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5 These calculations only include volumes of the storm where graupel is identified as the dominant type of hydrometeor.
between the jump and nonjump categories. The median growth rates of the 10 m s\(^{-1}\) updraft volume in the 0–2 and 2+ sigma-level categories are 16 and 62 km\(^3\), respectively (Fig. 2b). Wilcoxon–Mann–Whitney rank sum testing demonstrates that the two distributions are different. The \(Z\) score and \(p\) value for the 10 m s\(^{-1}\) updraft volume change are 1.987 and 0.0234, respectively (Table 2). Thus, the null hypothesis is rejected for the 10 m s\(^{-1}\) updraft volume, and larger increases in 10 m s\(^{-1}\) updraft volume are observed to statistically discriminate between lightning jumps and nonjump increases in total flash rate.

c. Peak updraft speed

Changes in the peak mixed-phase updraft speed reveal a major difference in the distributions of the two sigma-level categories (Fig. 3). The medians of the 0–2 and 2+ sigma-level categories are 1 and 5 m s\(^{-1}\), respectively, from the 1 km × 1 km × 1 km resolution data used in this analysis. Wilcoxon–Mann–Whitney rank sum testing shows that the two populations are different in Fig. 3. The \(Z\) score for the change in peak updraft speed is 3.286, with a \(p\) value of 5.0 \(\times\) 10\(^{-4}\). This indicates that the null hypothesis of similar distributions for jump and nonjump increases in total flash rate is rejected at the \(p = 0.05\) significance level (Table 2). Thus, a larger magnitude change in the mixed-phase maximum updraft speed in a thunderstorm is more likely associated with the development of a 2\(\sigma\) lightning jump than nonjump increases in the total flash rate.

d. Timing of increases

Figure 4 shows the difference in time between the time of 0–2 and 2+ sigma-level increases in total flash rate and the maximum increase in each of the three parameters (graupel mass, 10 m s\(^{-1}\) updraft volume, and maximum updraft speed). The time of the lightning increase is subtracted from the time of the peak increase in the three parameters to maintain a reference frame centered on the time of the lightning increase. In general, the largest increase in graupel mass, 10 m s\(^{-1}\) updraft volume, and maximum updraft speed during each 15-min analysis window is occurring on the order of 4–13 min prior to all increases in the total flash rate.

4. Discussion

a. The importance of peak updraft speed and 10 m s\(^{-1}\) updraft volume

Table 2 shows that the peak updraft speed is one of two parameters examined that demonstrates statistical independence between lightning jumps and nonjump increases in flash rate (the other being 10 m s\(^{-1}\) updraft volume). Therefore, the maximum updraft is not necessarily well correlated to the total flash rate over the entire lifetime of a thunderstorm, but the observations in this study indicate the increased likelihood that larger increases in maximum updraft speed are observed prior to the development of lightning jumps on shorter time scales (i.e., <15 min).
However, this discussion goes beyond the time scale at which correlations are made in these analyses. The peak updraft speed and 10 m s\(^{-1}\) updraft volume are found to be higher than the fall speeds of the ice hydrometeors responsible for electrification in thunderstorms. Ice crystals and graupel/small hail contribute to the electrification of thunderstorms and their typical fall speeds have been found to be ≤10 m s\(^{-1}\) (e.g., Dye et al. 1983, 1986; Musil et al. 1986; Musil and Smith 1989). The literature also shows that lightning propagation typically avoids regions of peak updraft speed and intense updraft volume as a result of lower concentrations of precipitation-sized ice and a lack of available charge (e.g., Wiens et al. 2005; Payne et al. 2010; Emersic et al. 2011; Calhoun et al. 2013; Kozlowski and Carey 2014). These regions are referred to as “lightning holes.” Therefore, the outstanding question remains: Why do these intense updraft characteristics matter to rapid lightning production?

Data from the 10 April 2009 case in Schultz et al. (2015) provide the best observational evidence of the importance of 10 m s\(^{-1}\) updraft volume and peak updraft speed working in combination to influence the total flash rate. Figure 5 shows a constant altitude plan position indicator (CAPPI) at 6 km and a north–south-oriented cross section through the most intense part of this developing supercell 8 min prior to lightning jump occurrence at 1720 UTC. Flashes during this period of time are primarily initiating in regions of...
weaker updraft (e.g., $<10\text{ m s}^{-1}$). Much of the lightning activity is to the north or south of the main updraft and contains convex hull-derived flash footprints$^6$ $\approx 50\text{ km}^2$. Figure 6 shows a north–south-oriented cross section through the same supercell at 1739 UTC, 9 min after two consecutive lightning jumps at 1728 and 1730 UTC. The highest density of flashes is now occurring above and along the sides of the core updraft region. The location observed to have the largest number of flashes also corresponds to the region where the smallest flash footprints are found. During this period of time, the $10\text{ m s}^{-1}$ updraft volume and peak updraft speed increase by over $100\text{ km}^3$ and $20\text{ m s}^{-1}$, respectively. Thus, it appears that the expansion of the $10\text{ m s}^{-1}$ updraft volume results in a larger three-dimensional volume of weaker updraft and a larger interface between the updraft and downdraft regions. This leads to more frequent lightning flashes with smaller flash footprints in regions around the thunderstorm updraft. These regions near the updraft are known for turbulent motion (e.g., Knupp and Cotton 1982; Pantley and Lester 1990; Lane et al. 2003; Bedka et al. 2015; Behnke and Bruning 2015).

The measurements within this study are not at sufficient spatial and temporal resolutions to examine this hypothesis beyond this inference. It is likely that the lightning jump is due to a combination of the increase in $10\text{ m s}^{-1}$ updraft volume (i.e., more cloud water, particle charging) and turbulence [i.e., smaller, more numerous charge regions; Bruning and MacGorman (2013)]; however, this hypothesis also relies on the ability of opposite charges to separate from each other. $^6$Flash footprint (i.e., approximate area the flash occupies in space) calculations are made in the same manner as in Schultz et al. (2015) using the convex hull methodology outlined in Bruning and MacGorman (2013).
other in regions of higher turbulence (e.g., Bruning and MacGorman 2013).

b. The less definitive role of graupel mass for lightning jumps

Another outcome of this study is that changes in graupel mass are not shown to be statistically robust indicators that separate jumps and nonjump increases in total flash rate. Figure 1 shows an increase in graupel mass during the 15 min prior to most increases in total flash rate. This indicates that graupel mass changes play a similar role for both jump and nonjump increases in total flash rate. Previous studies that show ice mass and total flash rates are well correlated over longer periods of time (i.e., the entire life cycle of the storm) also provide plausibility to this hypothesis. Deierling et al.’s (2008) Figs. 11 and 12 specifically illustrate that the same ice/graupel mass magnitude results in total flash rates that differ by as much as a factor of 10. This means that the relationship is not linear and one specific graupel mass does not result in one specific flash rate. Similarly, Schultz et al. (2015) show that similar changes in graupel mass result in different flash rates and DFRDT values (e.g., their Table 1). Therefore, the rate of change of the graupel mass is also not directly related to the rate of change of the flash rate.

c. Kinematic and microphysical characteristics of severe storms without jumps

The lightning jump algorithm in its current form will not be a stand-alone warning algorithm. There are several scenarios where severe weather is produced and lightning production is small or nonexistent (e.g., Butts 2006; Schultz et al. 2009, 2011). In fact, nearly 40\% (64/161) of the missed severe weather events by the lightning jump in Schultz et al. (2011) were due to cold season and tropical cyclone storms that produce very little lightning. These environments mainly consisted of very little thermally buoyant energy (e.g., $\text{CAPE} \leq 500 \text{ J kg}^{-1}$) and strong 0–3-km wind shear (not shown).

The 39-thunderstorm dataset contains 6 thunderstorms that fit the low-topped, cold season, or tropical classification, which also lack lightning jumps. All six of these storms are severe and produce hail, high winds, or tornadoes. The median (mean) increase in graupel mass for these types of severe storms is $1.96 \times 10^7 \text{ kg}$ ($3.54 \times 10^7 \text{ kg}$), and the median trend in graupel mass for these five storms falls below the 25th percentile for trends in graupel mass prior to lightning jumps of $2.31 \times 10^7 \text{ kg}$ (Fig. 1). Mixed-phase 10 m s$^{-1}$ updraft volume growth and peak updraft speed intensification are also weak. The median (mean) 10 m s$^{-1}$ updraft volume increase.
is 0 km$^3$ (15 km$^3$) for these types of severe storms. Furthermore, median (mean) increases in the peak mixed-phase updraft speed are only on the order of 0.4 m s$^{-1}$ (1.5 m s$^{-1}$) prior to their peak increase in total flash rate. Thus, there is a lack of mixed-phase updraft growth or a total absence of 10 m s$^{-1}$ updraft volume within this set of storms (three of the six cases have a 10 m s$^{-1}$ updraft volume of 0 km$^3$). Weaker magnitude changes in peak vertical velocity are also observed in these storms (Fig. 3). These weaker mixed-phase kinematic properties limit the storm’s potential to produce lightning and lightning jumps prior to severe weather occurrence.

The weak mixed-phase updraft magnitudes and changes in magnitude observed in this study are similar to those found in other shallow severe storms during previous observational and modeling studies (e.g., McCaul and Weisman 1996; Cantrell 1995; Knupp et al. 1998; Eastin and Link 2009). This indicates that severe weather production does not always require robust mixed-phase updrafts. This is why lightning trends in these types of storm may not always be useful for providing lead time on severe weather occurrence because of the limited size of the updraft or lack of strong mixed updraft speeds in cold season, low-topped, or tropical cyclone severe thunderstorm environments.

5. Conclusions

The results of this work provide a comprehensive statistical evaluation for physical parameters that are hypothesized to modulate electrification and lightning in thunderstorms. A large dataset of 39 thunderstorms with 214 analysis windows of 15 min are used to assess trends in mixed-phase graupel mass, updraft volume, and updraft speed prior to lightning jumps and other nonjump increases in the total flash rate. The following conclusions were made from this analysis:

- Graupel mass is not observed to be a statistically significant discriminator between lightning jumps (i.e., 2+ sigma level) and nonjump (i.e., 0–2 sigma level) increases in total flash rate. The one-tailed $p$ value for the independence test of the jump and nonjump distributions is $p = 0.096$.

- The change in 5 m s$^{-1}$ updraft volume is also not observed to be a statistically significant discriminator between lightning jumps and nonjump increases in the total flash rate. The one-tailed $p$ value for the independence test of the jump and nonjump distributions is $p = 0.093$.

- Larger increases in 10 m s$^{-1}$ updraft volume are observed for lightning jumps versus those observed with nonjump increases in the total flash rate ($p = 0.0234$). The median changes in 10 m s$^{-1}$ updraft volume for the jump and nonjump categories are 62 and 16 km$^3$, respectively.

- Larger-magnitude increases in peak updraft speed are observed for lightning jumps versus those observed with nonjump increases in the total flash rate ($p = 5.0 \times 10^{-4}$). The median changes in maximum updraft speed are 5 and 1 m s$^{-1}$ for jump and nonjump increases, respectively (Fig. 3).

- Very little difference is found in the timing between the peak increase in each of the three kinematic/microphysical parameters (mixed-phase graupel mass, 10 m s$^{-1}$ updraft volume, and peak maximum updraft speed) relative to the time of the total flash rate increase. In general, growth occurs between 4 and 13 min in advance of most flash rate increases.

- A sample of six severe thunderstorms that did not produce lightning jumps demonstrates that the main characteristic lacking in these storms is mixed-phase updraft. These storms lack significant changes in 10 m s$^{-1}$ updraft volume and the magnitude of the peak updraft speed in the mixed-phase region during their largest increases in total flash rate.

These strong statistical results support the use of lightning jumps to infer changes in stronger updraft characteristics in thunderstorms. Often these physical parameters are not readily available in operational datasets, and thus the lightning data can provide some indication of the trend of the mixed-phase updraft (growing versus weakening). Future work will need to demonstrate the physical connections between mixed-phase updraft growth and severe weather production in thunderstorms.

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APPENDIX

The 2σ Lightning Jump Algorithm

Although the lightning jump algorithm has been described in previous work (e.g., Schultz et al. 2009, 2011; Chronis et al. 2015), it is good to review the formulation of the algorithm for reference to this work. The primary source of lightning data for this algorithm has been lightning mapping arrays with the goal of ultimately utilizing GLM once GOES-R data are operationally available.

The algorithm starts with 14 min of total lightning data that have been assigned to a specific thunderstorm. For this example, \( t_0 \) is the most recent minute of data, and \( t - 13 \) is the oldest minute of data. First, 1-min flash rates are combined to produce an average flash rate every 2 min. For example, the average flash rate (FR) for time \( t_0 \) and time \( t - 1 \) is

\[
FR_{\text{avg}}(t_0) = \frac{FR_{t_0} + FR_{t-1}}{2 \text{ min}}, \quad (A1)
\]

while the average flash rate for times \( t - 12 \) and \( t - 13 \) would be

\[
FR_{\text{avg}}(t - 12) = \frac{FR_{t-12} + FR_{t-13}}{2 \text{ min}}. \quad (A2)
\]

Now there are a total of seven 1-min average flash rates: \( FR_{\text{avg}}(t_0), FR_{\text{avg}}(t - 2), FR_{\text{avg}}(t - 4), FR_{\text{avg}}(t - 6), FR_{\text{avg}}(t - 8), FR_{\text{avg}}(t - 10), FR_{\text{avg}}(t - 12) \). Next, subsequent \( FR_{\text{avg}} \) times are subtracted from each other to obtain the rate of change of the total flash rate, which is more commonly known as DFRDT. For the rate of change in the flash rate between \( FR_{\text{avg}}(t_0) \) and \( FR_{\text{avg}}(t - 2) \), the equation would be

\[
\text{DFRDT}_{t_0} = \frac{FR_{\text{avg}}(t_0) - FR_{\text{avg}}(t - 2)}{2 \text{ min}} = \text{DFRDT}(\text{flashes min}^{-1}). \quad (A3)
\]

while for \( FR_{\text{avg}}(t - 10) \) and \( FR_{\text{avg}}(t - 12) \), the equation would be

\[
\text{DFRDT}_{t-10} = \frac{FR_{\text{avg}}(t - 10) - FR_{\text{avg}}(t - 12)}{2 \text{ min}} = \text{DFRDT}(\text{flashes min}^{-1}). \quad (A4)
\]

Now there are a total of six DFRDT values for the algorithm to use to identify a lightning jump (DFRDT, DFRDT, DFRDT, DFRDT, DFRDT, DFRDT). The current rate of change of the total flash rate in the storm is DFRDT, while DFRDT, DFRDT, DFRDT, and DFRDT are used to calculate the standard deviation of the rate of change of the total flash rate in the storm between time \( t - 2 \) and up to (but not including) \( t - 14 \). The result is the sigma-level calculation found in Eq. (2). A sigma-level value \( \geq 2 \) identifies a lightning jump, while a sigma-level value \( < 2 \) is identified as a nonjump increase in the total flash rate. This representation of the 2σ lightning jump algorithm provides users with more information than the previous algorithm (i.e., a yes/no answer that the 2σ lightning jump threshold has been exceeded) by allowing the user to determine how far above or below any increase in total flash rate is relative to the dynamic 2σ threshold.

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