The Relationship between Total Cloud Lightning Behavior and Radar-Derived Thunderstorm Structure

ERIC METZGER AND WENDELL A. NUSS
Department of Meteorology, Naval Postgraduate School, Monterey, California

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ABSTRACT

Total lightning detection systems have been in development since the mid-1980s and deployed in several areas around the world. Previous studies on total lightning found intra- and intercloud lightning (IC) activity tends to fluctuate significantly during the lifetime of thunderstorms and have indicated that lightning jumps or rapid changes in lightning flash rates are closely linked to changes in the vertical integrated liquid (VIL) reading on the National Weather Service’s Weather Surveillance Radar-1988 Doppler (WSR-88D) systems. This study examines the total lightning and its relationship to WSR-88D signatures used operationally to determine thunderstorm severity to highlight the potential benefit of a combined forecast approach. Lightning and thunderstorm data from the Dallas–Fort Worth, Texas, and Tucson, Arizona, areas from 2006 to 2009, were used to relate total lightning behavior and radar interrogation techniques. The results indicate that lightning jumps can be classified into severe wind, hail, or mixed-type jumps based on the behavior of various radar-based parameters. In 25 of 34 hail-type jumps and in 18 of 20 wind-type jumps, a characteristic change in cloud-to-ground (CG) versus IC lightning flash rates occurred prior to the report of severe weather. For hail-type jumps, IC flash rates increased, while CG flash rates were steady or decreased. For wind-type jumps, CG flash rates increased, while IC flash rates either increased (12 of 18) or were steady or decreased (6 of 18). Although not every lightning jump resulted in a severe weather report, the characteristic behavior in flash rates adds information to radar-based approaches for nowcasting the severe weather type.

1. Background

Total lightning refers to all lightning in and between thunderstorms including in-cloud (IC) and cloud-to-ground (CG) lightning activity. The National Lightning Detection Network (NLDN) uses sferics via the very-low-frequency (VLF) and low-frequency (LF) radio bands to detect the CG strokes (Pierce 1977; Williams et al. 1989a, 1999). IC lightning can be detected and located through time of arrival analysis using high-frequency (HF) and very-high-frequency (VHF) radio bands. The first such system was developed by the National Aeronautics and Space Administration (NASA) at the Kennedy Space Flight Center in Florida and has been used operationally by the 45th Weather Squadron of the U.S. Air Force (USAF) and the National Weather Service (NWS) in Melbourne, Florida (Williams et al. 1999). A similar system was deployed operationally by New Mexico Institute of Mining and Technology at the National Space Science and Technology Center (NSSTC) Alabama in 2001 and has been utilized operationally by the NWS Forecast Office (NWSFO) in Huntsville since 2003 (Darden et al. 2010), where forecasters note a sudden increase in total lightning activity prior to the onset of severe weather. These lightning jumps occurred as much as 30 min prior to the occurrence of severe weather (Darden et al. 2010), confirming earlier studies by Williams et al. (1999) and Goodman et al. (2005). The observations from these prior studies and the Huntsville site led to the development of the total lightning system by Vaisala Incorporated to be deployed in various parts of the world including the Kennedy Space Center, Florida (KSC); Washington, D.C. (KIAD); Houston, Texas (KEFD); Paris, France (LFPG); Dallas–Fort Worth, Texas (KDFW); and Tucson, Arizona (KTUS).

Since the advent of total lightning detection systems, several studies have examined total lightning characteristics and behavior relative to severe weather. Goodman et al. (2005) found that severe thunderstorms

Corresponding author address: Wendell Nuss, Dept. of Meteorology, Naval Postgraduate School, Root Hall 254, Code MR/Nu, 589 Dyer Rd., Monterey, CA 93943-5114.
E-mail: nuss@nps.edu
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producing hail and tornadic activity tended to produce large amounts of IC and an increase in positively charged CG flashes. Total lightning systems have also examined powerful IC lightning strokes that have ionospheric reflections called narrow bipolar events that are frequently positive in polarity and may be a possible indicator of thunderstorm strength (Shao et al. 2006). Montanya et al. (2009) focused on the rapid increase in IC lightning prior to the onset of severe weather that results from the changing structure of severe thunderstorms. These previous studies as well as others provide some significant insight into the evolution of IC and CG lightning in thunderstorms that may help to identify severe or tornadic activity more efficiently when applied in conjunction with current operational radar methods.

Other studies by Williams et al. (1989b, 1999), Goodman et al. (2005), Wiens et al. (2005), and Steiger et al. (2007a,b) have focused on storm structure and relating changes in storm structure to total lightning evolution. Williams et al. (1999), using the Lightning Imaging Sensor Demonstration and Display (LISDAD) in central Florida, found that IC coincides better with maximum reflectivity in the mixed-phase layer than maximum cloud-top height (echo top). Changes in IC occurred abruptly with no immediate change in the radar return (Williams et al. 1999), indicating there is a delay between the sensible weather on the ground and the time of change in the IC lightning activity. Williams et al. (1999) also observed a tendency for increased IC lightning activity to precede downbursts by 1–15 min. Since downbursts require a strong updraft prior to the formation of the downburst, an increase in IC lightning indicates an increase in the strength of the corresponding updraft of the thunderstorm as it passes through the mixed-phase layer. The mixed-phase layer is a known area of significant charge separation and/or electrification indicating the updraft would be the primary area for IC lightning jumps (Uman 1987; Williams et al. 1999). These studies indicate the increase in IC lightning activity primarily occurs in the mixed-phase layer of the thunderstorm. Other studies have indicated the main area of the hail shaft is an area where IC lightning does not occur and that increased IC lightning concentrates on the edges of the main updraft and/or hail shaft (MacGorman et al. 2002; Steiger et al. 2007a; Boussaton et al. 2007). Goodman et al. (2005) and Wiens et al. (2005) found another important IC lightning and storm structure characteristic in tornadic thunderstorms, where areas of reduced or no lightning called lightning holes were nearly always associated with a bounded weak echo region (BWER) radar signature. These sudden changes in IC lightning activity and areas of a thunderstorm becoming void of lightning are some of the total lightning characteristics that NWS operational forecasters at Huntsville (Darden et al. 2010), Dallas (Demetriades and Patrick 2006), and Tucson, as well as Air Force weather forecasters (AFWF) at Davis–Monthan Air Force Base (DM AFB), Arizona, have noted when using the total lightning data.

Lightning jumps and their tendency to precede severe weather are related to updraft strength as noted in numerous previous studies. For example, MacGorman et al. (2002), Weins et al. (2005), Steiger et al. (2007a), and Montanya et al. (2009) have clearly shown lightning jumps are directly related to the strength of the main updraft of the thunderstorm as measured by the Weather Surveillance Radar-1988 Doppler (WSR-88D) reflectivity, which is a key indicator of the potential for severe weather. The lead time between a lightning jump and the occurrence of severe weather varies. Steiger et al. (2007a) indicate that lightning jumps occur between 5 and 30 min prior to the occurrence of a severe weather report on the ground with supercell thunderstorms. Goodman et al. (2005) indicate a similar result with lightning jumps in pulse storms occurring on average 12 min prior to severe weather occurring on the ground. Williams et al. (1999) also show this correlation where lightning jumps occurred 1–15 min prior to severe weather on the ground and lightning jumps preceded severe hail events by 7 min on average. While not all studies indicate consistent results of lightning jumps occurring prior to severe weather, the overall tendency for lightning jumps to precede severe weather in single, multicell, and supercell cases indicates that total lightning is a useful interrogation tool for operational forecasters. Recent studies by Gatlin and Goodman (2010) and Schultz et al. (2009, 2011) have examined the application of lightning trends to severe weather nowcasting and clearly indicate improved lead times and reduced false alarm rates in severe weather predictions using total lightning data. The present study examines the use of lightning jumps in concert with standard radar interrogation to refine the operational application of these data.

While past studies suggest a link between the changes in total lightning and thunderstorm characteristics, a clear relationship to severe storm radar interrogation procedures employed by the NWS and AFWF has not been established. Perez et al. (1997) found a direct link between IC and CG and tornadic activity during the 13 March 1990 Hesston, Kansas, tornado event that was rated as a category 5 storm on the Fujita scale (F5), but were not able to relate the increase in CG lightning directly to storm radar signatures. Other studies have also examined CG rates as a precursor to tornadic activity but have produced varied results, possibly indicating
that CG lightning may be regionally dependent (Perez et al. 1997; Carey and Rutledge 2003). Studies by Goodman et al. (2005) indicate that lightning holes should be "nearly always associated with a BWER" and work by Steiger et al. (2007a) shows that the heights of lightning flash initiation points strongly correlate with the vertical integrated liquid (VIL), and begin to relate lightning observations to common radar storm interrogation in the operational setting. Steiger et al. (2007a) also examined maximum reflectivity, several hail indices from the WSR-88D, including VIL, and VIL showed the best statistically significant correlation with lightning source height. It should be noted though that this method can only be applied to single or "stand alone" supercells or other severe thunderstorms and not to mesoscale convective system (MCS) or mesoscale convective complex (MCC) storms. In the MCC/MCS cases, the IC and CG lightning peaks showed significant variability in relation to the severe weather event, indicating no significant relationship between severe straight-line winds and total lightning could be found (Steiger et al. 2007b; Hodapp et al. 2008).

Finally, a key component to operationally applying any lightning techniques to severe weather identification is to easily identify IC and CG lightning jumps. Lightning jumps have been defined by Schultz et al. (2009, 2011), Gatlin and Goodman (2010), and others as an increase in the flash rate over time. Although the exact threshold used to identify a jump varies, Schultz et al. (2009) show that an 8 flash min$^{-2}$ threshold was a useful simple method. Schultz et al. (2009, 2011) and Gatlin and Goodman (2010) have tested a number of different lightning jump algorithms that show some significant promise in aiding the forecaster in automatically identifying lightning jumps prior to severe weather events in real-time data. Since the emphasis in this study is on examining the relationships between lightning jumps and radar signatures that might be most effective in a combined approach to severe weather nowcasts, a simple total lightning jump identification procedure and commonly used radar interrogation parameters are used. This study used a 10 flash min$^{-2}$ threshold, which Schultz et al. (2009) found to perform very similar to their 8 flash min$^{-2}$ threshold with fewer false alarms. The radar interrogation parameters used in this study include weak echo regions (WER), BWER, mesocyclone detection (MESO), rapid changes in the 55-dBZ height, maximum reflectivity, VIL, VIL density (VIL divided by echo-top height), and wind gust potential (WGP), which is an algorithm based on VIL and echo-top height. These parameters will be compared to the actual severe weather events and the behavior of the lightning jumps that preceded the events to determine a more robust combined approach to severe weather forecasting. Section 2 presents the data analysis and methodology used to quantify the behavior of lightning jumps examined in section 3 and their relationship to radar signatures in section 4. A summary and conclusions are given in section 5.

2. Data analysis and methodology

The thunderstorms selected for this study originated from KDFW and KTUS, due to their close proximity to a NWS WSR-88D radar system and available total lightning systems. The KDFW site is located in a heavily populated area with a WSR-88D radar system located just to the south of Fort Worth, which places the radar approximately 44 km to the southwest of the center of the Lightning Detection and Ranging II (LDAR II) total lightning detection system. The KTUS site is less populated and home to Vaisala Incorporated’s new total lightning LS8000 system with a WSR-88D radar system approximately 30 km to the southeast. The lower-population area around Tucson did have the drawback of producing fewer verifiable severe weather events.

The LDAR II system at the KDFW site was deployed in 2001 and employs nine lightning detection sensors detecting both IC and CG lightning. Carey et al. (2005) provide a detailed description of this system, which detects the radiation pulse from the electrical breakdown processes produced by lightning flashes. The time of arrival of the radiation pulse at multiple sensors is used to resolve the flash location but requires a minimum of four, and ideally five or more, of the nine sensors to detect and resolve the flash location to within 100–200 m (Carey et al. 2005). The LDAR II was primarily intended for research purposes rather than day-to-day operational use and increased sensor noise in heavy precipitation can disable or impair individual sensors causing brown-out conditions at times (Carey et al. 2005). If more than one sensor becomes impaired or disabled, the LDAR II will poorly resolve the IC lightning. Several prospective thunderstorm cases were discarded from this study due to sensor noise preventing resolution of the IC lightning pattern for the storm being interrogated.

The LS8000 is a commercial lightning detection system developed by Vaisala that was deployed in 2007 at the KTUS site. The main difference between the LS8000 and the LDAR II at KDFW is that the LS8000 is a two-dimensional system that uses an interferometric approach to detect and locate IC lightning along with a time of arrival approach to locate CG lightning. The system only requires four sensors for operation, with only two sensors needed to detect the flash and a minimum of three sensors to resolve its location, which
results in fewer sensor noise impacts due to heavy precipitation. Like the LDAR II, the LS8000 can detect both IC and CG lightning flashes, although the location accuracy of the LS8000 is only 1–2 km for IC lightning.

Both systems have an effective range of 100 km with the LDAR II system sometimes reaching 150 km (Carey et al. 2005) for cases in which all sensors are operating. The close proximity of the WSR-88D radar system to the lightning networks helped reduce the gaps in the scan elevation angles that are inherent with this radar system. This reduced artifact errors in the level III data, especially in VIL, which is particularly susceptible to these errors when the storm is farther away from the radar site. The close proximity to the radar site does have the disadvantage of the storm top breaking into the radar’s cone of silence if the cell is too close. These cases limited the measurement of some of the radar parameters, especially the 55-dBZ height. Fortunately, only four of the cases studied fell into this category. The vast majority of cases studied were in the optimal range of 25–120 km of the radar site, ensuring a solid volume scan at each time step.

Thunderstorms were selected based on the occurrence of severe weather within each site’s range of lightning detection from 2006 to 2009. Occurrences of severe weather were determined from the NWS local storm reports (LSRs) that were obtained from the National Climate Data Center (NCDC). Schultz et al. (2009) have noted time and location errors in the LSRs, which also occurred in this study and resulted in two cases being removed as there was no way to determine which thunderstorm cell produced the reported severe weather. For the purposes of this study, a severe weather event is defined as hail of 19 mm (3/4 in.) or greater, wind of 25 m s\(^{-1}\) (50 kt) or greater, or the occurrence of a tornado touchdown. Although the NWS standard for severe hail has changed to 25 mm (1 in.), the 19-mm (3/4 in.) standard was in use for the years examined in this study and is still used by the U.S. Air Force.

The use of level III data was the primary source of detecting changes in the VIL, echo top, MESO, and tornado vortex signatures (TVSs) of individual storms. These features were identified using rules governed by Part D of the NWS’s Federal Meteorological Handbook No. 11 (Office of the Federal Coordinator for Meteorological Services 2006, hereafter FMH-11) as updated in February 2006. The FMH-11 standards were also used to identify the changes in level II data as well. The identification of WER, BWER, bow echo, and storm-top divergence signatures and changes to the maximum reflectivity and the maximum height of the 55-dBZ reflectivity was governed by the FMH-11 as well as the derived parameters VIL density and WGP.

Once the thunderstorm cases were selected based on the occurrence of severe weather and the availability of the radar data, the lightning data were requested from Vaisala, who verified the data for integrity. Vaisala also provided their proprietary LTS2005 software for the interrogation of the lightning data. Figure 1 shows an image from the LTS2005 software for a severe hail event over Mineral Wells, Texas, on 30 March 2007. The image shows lightning branches derived from the individual lightning flash source points measured by the sensors. The connect-the-dot algorithm used to define flashes in the LTS2005 software has some inherent uncertainty in producing an accurate flash rate, and the flash rates are above those found in other studies. However, as noted by Wiens et al. (2005), the trend in total flash rates is still captured for a variety of flash source count thresholds to define an individual flash. Consequently, the flash rate changes were considered to be indicative of actual trends. The histogram in the bottom-left corner of Fig. 1 shows the flash rate observed over the area defined by the current field of view on the display for a specified sampling interval over six intervals. For purposes of this study, a 1-min sampling interval was used and the trend over the last 6 min of lightning history is displayed for the most recent time intervals ending at the times specified in the label bar in the top-right corner of Fig. 1. CG and IC lightning counts are accounted for separately. The histogram is what an operational forecaster would use to help identify a lightning jump.

For this study, individual cells were defined using the WSR-88D base reflectivity and the LTS2005 field of view was adjusted to encompass only the cell of interest. Every effort was made to limit or completely eliminate contamination from lightning activity from other cells. At each time step, the total lightning, IC, and CG flash rates were recorded. In the case of a squall-line MCS, only the individual storms easily distinguishable and their individual lightning characteristics were able to be singled out by the LTS2005 software with a minimum of lightning contamination from other cells. This occurred in only 2 of the 34 thunderstorm cases examined. In cases where individual storms were not easily distinguishable, the case was discarded.

For the interrogation phase of the study, the radar and lightning data were interrogated for each case at the time of the last sweep of a complete radar volume scan. At each time step (~5 min), the 1-min lightning flash rate over the past 6 min was entered into a spreadsheet for later analysis. In cases where cells were merging, lightning from other storms was unavoidable. The lightning from the colliding cell was then gradually included into the cell of interest. Once vigorous IC lightning
interaction between the two cells occurred, the lightning from each cell was then considered part of a single system. The complete inclusion of the lightning activity from the new colliding cell usually occurred before cells can be considered to have merged on radar. This subjective procedure for the gradual inclusion of lightning prevented lightning jumps from being introduced artificially into the data.

Lightning jumps were identified during this phase as an increase in the flash rate of 10 flashes min$^{-2}$ in either IC or CG flash rates, where the increase was sustained for at least 3 min. This definition of a lightning jump based on IC or CG and not total lightning differs from that used in other studies (e.g., Schultz et al. 2009, 2011; Gatlin and Goodman 2010, and others). This application to each component of the total lightning to define a jump was done to highlight potential storm structure differences that might be associated with IC or CG changes alone. In many cases, the total lightning also had a jump if either component produced a jump. For purposes of this study the time of the jump was assigned with the time of the initial increase, although detection would not have occurred until 3 min later. The 10 flash min$^{-2}$ increase rule worked well for most cases. In some cases, where overall lightning activity was less than 150 total flashes in a 6-min period, the storm either did not produce any lightning jumps or the lead time from the jump to the severe weather event was very short. At first, the lack of a lightning jump was thought to be normal for a nonsevere storm or low lightning activity severe weather cases. Figure 2 illustrates the lightning evolution that occurred in a high lightning activity storm, where the total lightning flash rate easily increased by 200 flashes min$^{-2}$ for some lightning jumps. In contrast, Fig. 3 illustrates the evolution in a low lightning activity storm in which the flash rate went from 10 to 80 flashes min$^{-2}$ in a very pronounced jump. Because the percentage change is much larger with low-activity storms, the jump often stands out more clearly, as seen in Fig. 3.

Although the lightning jump in Fig. 3 is quite evident, the identification of jumps in low lightning activity storms with a small absolute change in flash rate poses problems for any detection method. The lightning jump algorithm of Schultz et al. (2009, 2011) activates only after the total lightning reaches 10 flashes min$^{-2}$, which occurs part way into the lightning jump in Fig. 3. The algorithm used by Gatlin and Goodman (2010) would also detect the jump after several minutes once the
increase exceeded the average flash rate over the previous 6–10 min by more than a standard deviation. The method used in this study also results in a 3-min lag due to the required sustainment criteria. Other low lightning activity events, where no more than 150 flashes occurred in a 6-min period, typically failed to produce a jump even though subjective inspection of the time series suggested one occurred. For these cases, the 10-flash increase in a minute requirement was reduced to a 5 flash min$^{-2}$ increase in a minute. The 5 flash min$^{-2}$ increase in lightning activity still had to be sustained for a minimum of 3 min to be considered a jump. Although the lowered threshold does not reduce the time lag, the 5 flash min$^{-2}$ rule produced a jump in Fig. 3 as well as all low lightning activity cases that would have not been identified using the higher threshold. The reduced flash rate increase was chosen arbitrarily and is dependent on absolute flash rates in this study, which appear to be biased high relative to other studies. This introduces uncertainty into the process of setting lightning jump thresholds based on absolute flash rates and should be more thoroughly tested.

For the radar data, an interrogation of each elevation scan of the cell of interest was conducted at the end of each volume scan. This interrogation approach was done due to a software limitation that did not allow us to display of radar cross sections. In most cases, a time step was roughly every 4.5–5 min (VCP 11 and 12 scan setting), and in a few cases it was roughly 6 min (VCP 21 scan setting). Information from the cell of interest was collected at each time step to include the maximum reflectivity (dBZ), maximum height of the 55-dBZ contour (in meters and had to occur on each subsequent scan elevation and not be broken into vertical segments), VIL, echo top, VIL density, WGP, WER, BWER, MESO, storm-top divergence, and TVs signatures. The condition of a contiguous 55-dBZ column was mandated for this study to ensure frozen hydrometeors throughout the column, as it is known that reflectivities greater than 55 dBZ are the result of frozen hydrometeors in the form of graupel or hail of any size (FMH-11) rather than liquid hydrometeors alone. The 55-dBZ parameter was also chosen based on past studies that indicate storms with dBZ > 55 had a much greater chance for high lightning activity and severe weather (Boussatan et al. 2007). Additionally, if there is a contiguous column of 55 dBZ, it can be reasonably assumed there are higher reflectivities within the column. The VIL densities and WGP were recorded for comparison and to test their relationship to lightning jumps as USAF weather forecasters heavily use these parameters.

A standardized anomaly of the flash rates was calculated for each data sample based on the length of time the thunderstorm was active (thunderstorm life cycle). The standardized anomaly has the advantage of setting the mean of the data sample to zero, and places parameters on the same scale, making relationships between various parameters easier to identify. The standardized anomaly was used to aid in looking for relationships between the IC and CG flash rates when the IC lightning far exceeded the CG flash rate total. The standardized anomaly had one disadvantage in cases where CG lightning was very low or actually ceased for
more than 10 min at a time, exaggerating small increases in CG lightning.

Each lightning jump was then classified into one of three types: hail, wind, and mixed. No tornado-type jump was defined due to a lack of tornado events. The particular jump type was defined based on changes above a predefined threshold using the radar scans immediately preceding or following a jump in at least two of the following radar parameters: maximum reflectivity, 55-dBZ height, VIL density, VIL, echo top, and WGP. A change of 305 m in 55-dBZ height, 10 kg m\(^{-2}\) in VIL, 0.5 g m\(^{-3}\) in VIL density, 3050 m in echo top, and 7.5 m s\(^{-1}\) in wind gust potential in a single volume scan. The wind gust potential is based on the VIL and echo-top height and follows the method developed by Stewart (1991).

A hail-type jump is defined as a lightning jump in which the radar shows a sufficiently large increase in the volume scan immediately preceding or following the jump in at least two of the following: maximum reflectivity, 55-dBZ height, VIL density, VIL, echo top, and WGP. A change of 305 m in 55-dBZ height, 10 kg m\(^{-2}\) in VIL, 0.5 g m\(^{-3}\) in VIL density, 3050 m in echo top, and 7.5 m s\(^{-1}\) in wind gust potential in a single volume scan. The wind gust potential is based on the VIL and echo-top height and follows the method developed by Stewart (1991).

A wind-type jump was defined as a sufficiently large decrease in at least two of the same parameters mentioned for the hail type of jump. Figure 7 shows a drop in 55-dBZ height after the first lightning jump and an even more definitive drop prior to and after the second jump. Figure 8 shows a clear drop in VIL prior to the second jump and an echo-top increase following that jump, which results in decreases in VIL density both prior to and following the second jump, as shown in Fig. 9. FMH-11 and USAF Tech. Note 98-002, as well as Frazier (1994), indicate these are signs of a collapsing thunderstorm, and severe wind events often follow these changes, resulting in the wind-type classification for this study.

The third type of jump was called mixed as either only one parameter met the criteria or there were conflicting

FIG. 4. The 55-dBZ height (m) with the time of lightning jump indicated by a vertical solid line. Time of a hail event is indicated by dashed vertical line.

FIG. 5. VIL (solid, kg m\(^{-2}\)) and echo top (dashed, 1000s of m) results. Time of lightning jump is shown by a solid vertical line and time of hail event by a dashed vertical line.

FIG. 6. The VIL density (solid, g m\(^{-3}\)). Time of lightning jump is shown by a solid vertical line and time of hail event by a dashed vertical line.
readings within the storm (e.g., 55-dBZ height increased but VIL decreased).

The lightning jump data were also compared to the start time of several radar-derived storm structures which included WER, BWER, MESO, TVS, and storm top divergence. These structures and signatures were chosen because they are among the primary parameters used to gauge thunderstorm severity (e.g., Burgess and Lemon 1990).

Each thunderstorm case was categorized into the following categories in order to examine the lightning behavior under various conditions: severe, nonsevere, and high and low lightning activity storms. High and low lightning activity storms included both severe and nonsevere cases and were solely based on the lightning activity of the individual storm. The determination of severe and nonsevere cases depended solely on the reports of severe weather on the ground. The lightning jumps were categorized in each thunderstorm case based on what the IC and CG lightning behavior was like at the time of the jump with respect to each other. They were separated into the following groups: IC increasing while CG decreasing (or steady), both IC and CG increasing, or IC decreasing (or steady) while CG increasing. Although both IC and CG could be decreasing for a given thunderstorm, changes of this type were not identified as a jump.

3. Lightning jump characteristics

A total of 73 lightning jumps were identified in 34 thunderstorm cases, where 34 lightning jumps were classified as hail type, 20 were classified as wind type, and 19 were classified as mixed based on the radar data. Note that the lightning jump was identified first and then the radar signature was used to classify the jump. It is important to note that a severe weather event did not follow every lightning jump and this happened for all three types. In many cases, a second lightning jump followed an initial lightning jump. As a result, there was a much higher number of lightning jumps than there were severe weather events. From the 34 thunderstorm cases and 73 lightning jumps, there were 40 severe weather events comprised of 17 hail events, 18 wind events, and 5 tornado events. In some of the cases, there were multiple severe weather events from one storm.
and, at times, multiple severe weather events following a single jump. To better understand how lightning jumps potentially relate to types of severe weather when used in conjunction with radar data, each jump-type classification was examined in more detail.

Of the 34 hail-type jumps, only 18 directly preceded a severe weather report, with an average lead time of 11 min (14 min minus the 3 min needed to identify the jump). Of the 18 severe weather reports directly following a hail-type jump, 14 produced hail, 3 produced winds, and 1 a tornado. For the 34 hail-type jumps, 25 showed IC increasing while CG was decreasing (or steady). In some cases, the CG would cease entirely. This pattern of behavior is consistent with an increasing updraft and associated hail production, as noted by Williams et al. (1999) and others.

Figure 10 from Lakeside, Texas, illustrates the relationship between IC and CG lightning during a hail-type jump. The second lightning jump in Fig. 10 shows IC lightning increasing to produce the 10 flash min$^{-2}$ threshold, while the increase in CG lightning suddenly comes to a stop and becomes steady. The first lightning jump in Fig. 10 was triggered by an increase in CG lightning and was classified as a wind type (discussed later), the second jump was triggered by an IC lightning increase and was classified a hail-type jump. Not all lightning jumps classified as hail type directly preceded a hail event, as three directly preceded a severe wind event. Two of the three hail-type jumps identified that directly preceded severe wind events also produced hail. The time difference between the wind and hail reports was less than 6 min. Figure 11 illustrates an event from Oro Valley, Arizona, where severe wind and hail occurred in very close time proximity. The last lightning jump, classified as a hail-type jump, occurred 12 min prior the wind event; then 5 min later, the hail was reported. The wind and hail events occur so close together that they could be considered a single severe event. For this study, they were separated as they produced two different types of severe weather and also to illustrate that a hail-type jump is not exclusive to hail production.

Figure 11 also illustrates that there can be multiple lightning jumps in a thunderstorm and, in this case, only one of them was followed in a meaningful way by a severe weather event. Therefore, if lightning jumps were the sole source for predicting severe weather, then false alarms could occur when no severe weather followed, as suggested by the first two jumps in Fig. 11 that precede the severe weather by 45–60 min. Figures 10 and 11 also indicate a pattern of behavior between the IC and CG lightning with a hail-type jump where the IC lightning was the primary factor showing an increase while the CG lightning activity remained steady or decreased. This characteristic is more easily seen when the IC and CG flash counts are plotted against each other in a standardized anomaly chart. Figure 12 shows the nature of the IC and CG relationship during a hail-type jump at Littleton, Arizona, where the IC and CG standardized anomaly lightning plots begin to diverge at the time of a hail-type lightning jump and prior to the hail event.

The IC and CG behavior noted in Figs. 10–12 was the dominate pattern noted for the hail-type jumps. It occurred in 25 of the 34 hail-type lightning jumps, yielding nearly a 3:1 preference for the hail-type jump to display...
IC increasing while CG either remained steady or decreased. For the 18 hail-type jumps that directly preceded a severe weather event, 14 directly preceded hail, yielding a 3.5:1 ratio of hail occurring over wind or tornadic activity.

Not all hail-type jumps produced hail. Figure 11 shows a wind event occurring at nearly the same time as the corresponding hail event. In some cases, only severe wind was produced. In Fig. 13, a hail-type jump occurred 11 min prior to a severe wind event. The IC and CG are both increasing instead of only the IC increasing, which differs from the IC–CG characteristics of the other hail-type jumps. The case in Fig. 13 was a hail-type jump that only produced wind. Additionally, there were eight other hail-type jumps that also exhibited this same IC and CG behavior, but only three of them directly preceded a verified hail event. So this study cannot conclude that IC increasing and CG decreasing (or steady) is solely a characteristic of the hail-type jump, only that it tends to strongly favor hail over other types of severe weather.

Wind-type lightning jumps occurred 20 times and the IC and CG lightning behavior was examined in the same manner as for the hail-type jumps. Of the 20 wind-type jumps, 12 jumps had both IC and CG increasing while 6 jumps had CG increasing as IC was decreasing (or steady). The results indicate CG rarely decreased with wind-type jumps and IC either increases along with the CG or remains steady. This makes a ratio of 9:1 against CG falling during a wind-type lightning jump. Of the 20 wind-type jumps identified, there were 12 where severe weather events followed them. Two of them were hail events, seven were wind events, and there were three tornado events. The results suggest that the wind-type jumps tend to produce wind events.

Figure 14 shows the relationship between IC and CG lightning during a wind-type jump. In Fig. 14, the IC lightning activity actually decreases and is rapidly overtaken by the CG lightning activity to produce the jump. Figure 15 shows the indicated wind-type lightning jump relationship when the IC and CG lightning activity trends are plotted against each other in a standardized anomaly chart. Figure 15 shows the IC and CG lightning plots crossing each other, with the CG increasing just prior to 2330 UTC on the plot. For this storm, CG lightning changes appear to be the dominant factor preceding the wind event.

![FIG. 12. Standardized anomaly of IC and CG flash rates. Time of lightning jump is shown by a solid vertical line and time of hail event by a dashed vertical line.](image1.png)

![FIG. 13. Lightning flash rates in flashes per minute with times of lightning jumps indicated by solid vertical lines. Flash rates for total (solid), IC (dashed), and CG (dashed–dotted) lightning. Time of severe wind event indicated by a dashed–dotted vertical line.](image2.png)

![FIG. 14. IC and CG lightning during a wind-type jump. Lines and labeling are as in Fig. 13.](image3.png)
Most wind-type jumps displayed the IC and CG lightning activity increasing at the same time. Some of the time, the rate of increase appeared to be the same, but in many cases the rate of increase of CG tended to be greater than the IC, or opposite as in Figs. 14 and 15. Both jumps in Fig. 16 show the CG increasing after an initial increase in IC with the CG increasing more slowly in the first jump or at about the same rate as IC for the second jump. Figure 16 also shows the CG lightning increase is sustained for a longer period of time for both jumps. The CG increase for 2–6 min longer than an IC was a common trait in the wind-type jumps. Only 5 of the 20 wind-type jumps did not display a sustained increase in IC lightning activity that was longer than the sustained increase in IC lightning activity. The standardized anomaly plot in Fig. 17 shows that the CG increase is sustained for 3 min longer than the IC increase and even continues past the severe weather event, which was not a common characteristic of any of the lightning jumps. In most cases, the lightning activity would decrease or at least level off within 10 min of a severe weather event.

The results from the wind type jumps, like the hail-type jumps, suggest a relationship between the changing storm structure as seen on radar and the characteristics of the lightning. For the wind-type jumps, 18 of the 20 had CG lightning increasing and CG lightning tended to be the primary contribution to the lightning jump. In 12 of the 18 cases, IC and CG would increase together while 6 of the 18 had IC decreasing or steady. This pattern of lightning behavior is consistent with an increasing downdraft that lowers the charged region to produce more CG lightning (e.g., Williams et al. 1989b). The remaining 19 lightning jumps out of the 73 total could not be classified as being either the hail or wind type due to the fact the radar either showed no consistent changes in the key parameters or showed conflicting changes in the key parameters. The mixed-type lightning jumps were categorized in the same way as the hail and wind types. Of the 19 lightning jumps classified as mixed, 8 displayed IC increasing while CG was decreasing (or steady), 7 displayed both IC and CG increasing, and 4 displayed IC decreasing (or steady) while CG was increasing. The wide dispersion of characteristics indicates there was no predominate IC and CG pattern of behavior, as was the case for the hail- and wind-type jumps displayed. Nine of the 19 mixed lightning jumps directly preceded a reported severe weather event. Five of the events were severe wind, three were hail, and one was a tornado.
To illustrate the complexity of mixed-type events, Fig. 18 depicts a case where IC and CG lightning behavior is typical of a hail-type lightning jump even though a wind report occurred. The jump in Fig. 18 was classified as a mixed type as there was a consistent increase in echo top causing a significant decrease in VIL density that met the threshold criteria. The 55-dBZ height only showed a small change and did not meet the criteria as did the increase in VIL. The jump in Fig. 18 occurred 5 min prior to a 70-kt wind event, illustrating severe weather events do occur in these cases. The radar also indicated a BWER and MESO signature 15 min prior to the severe wind event. The pattern of the lightning traces in Fig. 18 is even more like a hail-type jump when it is plotted in a standardized anomaly chart. Figure 19 shows the CG lightning plot rapidly dropping below the IC lightning plot.

4. Radar signatures/structures and lightning activity

To confirm the relationship between common thunderstorm parameters from the WSR-88D and lightning jumps found in previous studies and utilized in the previous section, the severity of thunderstorms with radar data was interrogated first and then any lightning jumps were noted. Specifically, are the lightning jumps a reaction to the parameters developing in a given thunderstorm, or are they a precursor to or have no identifiable relationship to subsequent thunderstorm evolutions? Some problems became apparent in this analysis as many of the parameters were already present in the thunderstorm well prior to any of the lightning jumps, or were too few in number to determine any sort of relationship. Storm-top divergence showed no consistent relationship to lightning jumps. The WER signature tended to show no consistent relationship either but it should be noted that for many of the cases a WER was already present when the storm came into range of the lightning detection system. The TVS and bow echo signatures could not be evaluated as there were too few cases to evaluate (TVS had four and bow echo had two). The BWER, MESO, 55-dBZ height, VIL, and VIL density signatures tended to occur near the time of the lightning jumps and were rarely already present when the storm entered the lightning detection system’s range.

The BWER signature is one of the more significant severe weather signatures operational forecasters look for in gauging the severity of a thunderstorm. Additionally, BWER signatures are well known to frequently be present in severe hail and tornado-producing storms (Burgess and Lemon 1990). In this study, 15 cases displayed a BWER signature. In all 15 cases, the start of the BWER pattern occurred within 15 min of the lightning jump, with an average time difference of 7.4 min. This is close to the time period the WSR-88D takes to produce a complete volume scan. In three of the cases, the BWER occurred after the lightning jump while in most cases (12), the BWER occurred before the lightning jump. The time lag in radar sampling relative to the lightning evolution may account for the three cases where the jump led the development of a BWER. The implication of this result to nowcasting is that the radar signature provided the first alert to severe weather and that the lightning jump then adds subsequent information about the potential type of severe weather.

The MESO signature was another radar parameter that frequently signifies a severe thunderstorm (e.g., Duda and Gallus 2010) and should show a consistent

![Fig. 18. Lightning flash rates for a severe wind event. Lines and labeling are as in Fig. 13.](image1)

![Fig. 19. Standardized anomaly of IC and CG for same event as Fig. 18. Lines and labeling are as in Fig. 15.](image2)
relationship to lightning jumps. The MESO parameter was carefully looked at to make sure there was enough evidence on radar to classify a mesocyclone, and was done in accordance with FMH-11. FMH-11 requires a minimum 10 m s\(^{-1}\) difference between the in- and outbound maximum radial winds, occurs at three consecutive levels, and be sustained for at least two volume scans. Twelve storms met these criteria. The mesocyclone parameter showed the same relationship between its onset and lightning jumps as the BWER signature. All 12 cases had a lightning jump within 15 min of the MESO signature with an average of 9.5 min between the jump and the MESO signature. Although the time between the MESO and lightning jump is larger than that found for BWER, it is close to the time required for two volume scans, indicating a relationship between the mesocyclone formation and lightning activity in the storm.

The six other radar-derived parameters commonly used by operational forecasters to determine the severity of a thunderstorm are maximum reflectivity, 55-dBZ height, VIL, echo top, VIL density, and WGP, which is derived from the VIL and echo top (Stewart 1991). Of these six parameters, only 55-dBZ height, VIL, and VIL density showed consistent and systematic changes around the time of a lightning jump. The lack of a relationship between echo top and lightning jump duplicates the finding of Williams et al. (1999) that maximum lightning activity does not correspond with maximum cloud top. WGP failed to show any relationship with lightning jumps for all 34 thunderstorm cases and, even worse, failed to indicate severe wind in all 25 severe cases studied.

Earlier in this study, 55-dBZ, VIL, and VIL density were grouped together and required to have more than one of them displaying the same pattern of behavior when classifying the individual lightning jumps. Here, they are evaluated individually in an attempt to see if there is any direct relationship between 55-dBZ, VIL, and VIL density and lightning jumps.

a. 55-dBZ height

The 55-dBZ heights were examined in 31 of the 34 cases. The other three cases could not be included as one had errors in the 55-dBZ height data and two were too close to the WSR-88D at the time of the lightning jumps where the cloud tops were artificially low and could not be determined due to the cone of silence effect. In the 31 cases, there were 69 lightning jumps. Sixty-four of the lightning jumps either preceded or followed an increase (Figs. 20 and 21) or decrease (Fig. 22) in 55-dBZ height that exceeded the threshold and were detected on radar within 10 min of the lightning jump. For the other five jumps, there was either an increase or decrease in the 55-dBZ height on the radar but it did not meet the 305-m change threshold. For the five cases in which the 55-dBZ height changes were too small, all five occurred when the 55-dBZ height was at or above 6100 m. This was very close to the \(-20^\circ\)C level in nearly all cases. The very cold temperatures at this height could explain why the changes in the height were not as large because the 55-dBZ height may have already been at the maximum height possible for that particular storm.

In the 69 lightning jump instances, 57 of the lightning jump events were within 10 min of an increase in the 55-dBZ height while 12 occurred near a decrease. This yields a 4.75:1 ratio of the 55-dBZ height increasing
when a lightning jump occurs. The preponderance of the 55-dBZ height increasing indicates there is a direct relationship to the 55-dBZ height rising at the time of a lightning jump. This reasoning is consistent with previous studies, which indicate that charged areas of the cloud can be advected to other areas of the cloud by the updrafts and downdrafts within the thunderstorm bringing the charged regions closer together to initiate lightning (Steiger et al. 2007a,b; Montanya et al. 2009).

b. VIL and VIL density and lightning jumps

VIL values are heavily used by the operational forecasters as it has been shown that rapid changes, especially increases, in VIL indicate a storm is intensifying and hail is present. Additionally, high values of VIL generally indicate a very dense column of water or ice present in the storm (FMH-11; USAF Tech. Note 98-002). VIL density is another parameter used by the USAF and takes into account echo top. Thunderstorms with VIL density values over 3.5 g m\(^{-3}\) are considered to be at risk of having large hail (>19 mm) and values over 4 g m\(^{-3}\) are considered to be at high risk. Due to the similarities between VIL and VIL density, these parameters are examined together.

For VIL and VIL density, there were 73 lightning jumps to examine. In the VIL case, 49 showed a rise in VIL near the jump, while 17 showed a decrease and 7 did not show any net change. Figure 23 shows both a decrease and an increase in VIL associated with two different lightning jumps. Figure 24 shows lightning jumps that had an increase, decrease, and no change in VIL. VIL density showed something similar with 46 jumps related to an increase in VIL density, 24 showing a decrease, and only 3 showing no change at all. Figure 25 illustrates the VIL density changes for the same lightning jumps in Fig. 24. Both an increase at 1931 UTC and decreases at 1950 and 2010 UTC in VIL density are found. Given the results of the VIL and VIL density and lightning, it is difficult to say if a lightning jump is either the result of an increase in VIL value or a decrease in echo top causing the VIL density to increase. Clearly, lightning jumps are related to changes in VIL and VIL density. Additionally, VIL density appears to be more sensitive, as there were half as many cases with no change in VIL density near a jump compared to cases with no change in VIL. Like the 55-dBZ parameter,
specific increases or decreases in VIL and VIL density could not be considered a precursor or reaction to lightning jumps, although increases in VIL and VIL density tended to follow a lightning jump, which is probably due to the radar time sampling frequency as this differs from the results of other studies (Goodman et al. 2005, Gatlin and Goodman 2010) that show VIL increases preceding or very close to the lightning jumps.

5. Summary and conclusions

This study has confirmed that lightning jumps tend to precede the occurrence of severe weather on the ground, as has been found in many previous studies (Goodman et al. 2005; Shao et al. 2006; Montanya et al. 2009; Pierce 1977; Williams et al. 1999; Steiger et al. 2007a; Schultz et al. 2009, 2011; Gatlin and Goodman 2010). However, by using radar signatures to classify lightning jumps into three types (hail, wind, and mixed), the individual patterns of behavior of the IC and CG lightning activity for each individual storm revealed a specific relationship between lightning behavior and the type of severe weather. This relationship is summarized in Table 1, which shows the characteristic changes in radar parameters used to classify a lightning jump and the IC and CG lightning behavior for a particular type of severe weather.

This study has shown that hail events tended to be preceded by a lightning jump in which the IC lightning would increase while the CG lightning decreased or remained steady and when the radar signatures were displaying hail indications like a rapidly increasing VIL, VIL density, or increasing 55-dBZ height. Many of the hail-type jumps also occurred in close time proximity to the development of a BWER signature, which has been noted to occur frequently with lightning holes (e.g., Weins et al. 2005; Steiger et al. 2007a). Examination of the nonsevere hail cases clearly indicates that hail-type lightning jumps and radar signatures occurred in nonsevere events as well. Presumably, hail below the severe threshold occurred but could not be confirmed with observations.

Severe wind events tended to be preceded by lightning jumps in which both IC and CG would increase or the IC would decrease or remain steady while the CG increased. The radar signatures for wind events differed from hail events in that two of the VIL, VIL density, or 55-dBZ height signatures showed rapid decreases. Although this pattern of radar and lightning changes was fairly consistent in wind events, it should be noted there were three severe wind events that occurred directly following a hail-type lightning jump.

The mixed-type lightning jump had an even distribution of types of severe weather occurrences following them, so it is difficult to draw any definite conclusions about them except that mixed-type lightning jumps can produce all three types of severe weather: hail, wind, and tornadoes. In this study, the mixed-type lightning jump preceded two of the five tornadoes, while the wind type preceded two tornadoes, and the hail type preceded one tornado. The tornado sample is too small to determine if

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**Table 1. Radar and lightning behavior at time of lightning jumps associated with severe hail or winds.**

<table>
<thead>
<tr>
<th>Radar signature</th>
<th>Severe hail</th>
<th>Severe wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIL change threshold (10 kg m⁻² per volume scan)</td>
<td>VIL, VIL density, or 55-dBZ height</td>
<td>VIL, VIL density, or 55-dBZ height</td>
</tr>
<tr>
<td>VIL density change threshold (0.5 g m⁻³ per volume scan)</td>
<td>Two parameters must increase by listed thresholds</td>
<td>Two parameters must decrease by listed thresholds</td>
</tr>
<tr>
<td>55-dBZ height change threshold (305 m per volume scan)</td>
<td>IC increasing</td>
<td>CG increasing</td>
</tr>
<tr>
<td>Lightning behavior</td>
<td>CG decreasing or steady</td>
<td>IC increasing (most often) or decreasing/steady</td>
</tr>
</tbody>
</table>
the mixed type is the preferred type of jump for tornadoes. The fact that CG lightning decreased or ceased during tornado events was a similar finding from a previous study during violent (F4–F5) tornadoes (Perez et al. 1997).

This study shows that thunderstorms, both severe and nonsevere, will produce lightning jumps, similar to previous studies (e.g., Williams et al. 1999; Goodman et al. 2005; Schultz et al. 2009, 2011 ). However, we found that reducing the jump threshold to 5 flash min\(^{-2}\), when the overall lightning activity in a thunderstorm was less than 150 flashes in 6 min, helped identify lightning jumps in some of the 34 thunderstorms examined and identified a jump as much as 5 min earlier than when a 10 flash min\(^{-2}\) was used. This reduced threshold for low lightning activity storms seems justified given that the lightning jumps occurred within 10 min of the same radar-derived changes in intensification and collapse tendencies as the high lightning activity cases using a higher threshold. A noted previously, the flash rates in this study appear to be high and so the thresholds used to distinguish between low- and high-activity storms apply only to this study. Further study should be done to automate the jump identification, such as has been done by Schultz et al. (2011) or Gatlin and Goodman (2010) and to add some scaling of the identification based on lightning activity, as noted by Schultz et al. (2011) also.

One general trend in lightning activity that was not related to any particular radar signature was that overall lightning activity tended to decrease around the time of a severe weather event. The fall in lightning activity was especially apparent after wind and hail events. The lightning would then increase again in cases where there were multiple severe weather events. Steiger et al. (2007a) found a similar pattern of behavior. The sudden decrease in lightning activity could give the forecaster an earlier warning that a storm is decaying if the trend of decrease is long enough but again would have to be confirmed by further radar interrogation.

Of the six radar-derived parameters other than the BWER and MESO examined in this study, only three showed direct relationships with lightning jumps. These relationships also tended to be precursors to the type of severe weather that occurred. The hail- and wind-type lightning jumps showed strong direct relationships to 55-dBZ height, VIL, and VIL density. The relationship should not be unexpected since increases in the 55-dBZ height, VIL, and VIL density are known factors for hail production and tend to occur prior to severe hail events while decreases, especially significant decreases in these parameters, tend to occur in a thunderstorm prior to severe winds, especially downbursts (FMH-11; USAF Tech. Note 98-002).

It is important to note that any single parameter alone showed changes of both signs and cannot be used to classify the lightning jump type. The 55-dBZ heights, VIL, and VIL density parameters must be used in conjunction with each other to classify the lightning jumps. The other three parameters (maximum reflectivity, echo top, and WGP) failed to show a strong relationship in this study but do warrant further examination with a larger sample as these parameters are already used by operational forecasters.

Considering all the results of this study, a strong relationship between the character of lightning jumps and the structural changes of thunderstorms as revealed by radar is clearly suggested. Lightning jumps may be classified as hail, wind, and mixed types based on observed changes in the following radar signatures: 55-dBZ height, VIL, VIL density, BWER, and MESO. Using this classification, the preponderance of lightning jumps of a particular type (hail, wind, or mixed) tend to precede that particular type of severe weather with an average lead time of more than 10 min, and with less the 3 min needed to identify a jump using the simple jump algorithm of this study. A larger sample of storms would help to refine the estimated forecast lead time and could examine the probability of detection and potential for false alarms that was not feasible in this limited sample of events. However, the results in this study support those of other studies that total lightning behavior characteristics can add to severe-weather-type nowcasting that relies heavily on radar signatures and suggest that the IC and CG trends at the time of a lightning jump add useful information to the forecast process.

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