Radar Nowcasting of Total Lightning over the Kennedy Space Center

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ABSTRACT

A long-term radar dataset over Melbourne, Florida, was matched with three-dimensional lightning data to optimize radar-derived predictors of total lightning over the Kennedy Space Center (KSC). Four years (2006–09) of summer (June–August) daytime (about 1400–0000 UTC) Weather Surveillance Radar-1988 Doppler data were analyzed. Convective cells were tracked using a modified version of the Storm Cell Identification and Tracking (SCIT) algorithm, and correlated to cloud-to-ground (CG) lightning data from the National Lightning Detection Network (NLDN) and grouped intracloud (IC) flash data from the KSC Lightning Detection and Ranging (LDAR) I and II networks. Reflectivity values at isothermal levels and a vertically integrated ice (VII) product were used to optimize radar-based forecasting of both IC and CG lightning. Results indicate the best reflectivity threshold predictors of CG and IC lightning according to the critical success index (CSI) were 25 dB$Z$ at 220°C and 25 dB$Z$ at −15°C, respectively. The best VII predictors of CG and IC were the 30th (0.840 kg m$^{-2}$) and 5th percentiles (0.143 kg m$^{-2}$), respectively, suggesting less ice mass is needed in the main mixed-phase region for IC flashes to occur. In addition, VII at lightning initiation (both CG and IC) was higher than at cessation. Seventy-six percent of cells had IC initiation before CG initiation. Using the first IC flash as a predictor of CG occurrence also statistically outperformed other CG predictors, but yielded a 2.4-min average lead time. However, this lead time is comparable to the reflectivity threshold and VII methods when accounting for radar scan and processing time.

1. Introduction

Lightning remains a significant threat to human lives and property, even with continued improvements in our ability to observe and predict the weather. From 1959 to 1991, lightning ranked second only to river and flash floods in weather-related deaths per year in the United States (Curran et al. 2000). More recently (1981–2010) lightning was third only to floods and tornadoes with 55 fatalities per year, according to the National Weather Service’s (NWS) 2010 data on weather fatalities, injuries, and damage statistics.

Lightning poses the greatest threat to Florida. Coined the “lightning capital” of the United States, the state’s maritime influences and the persistence of tropical air masses provide an environment often conducive to the formation of thunderstorms. Florida has more than twice the number of lightning deaths as any other state (Curran et al. 2000), with at least two-thirds of casualties (fatalities plus injuries) occurring during the summer months of June–August (JJA). Furthermore, two-thirds of casualties occur between 1200 and 1800 local standard time (LST), during the climatological diurnal maximum of thunderstorm activity and peak of outdoor human activity.

Within Florida, a band of maximum annual cloud-to-ground (CG) lightning flash densities has been found to occur, with an area of 10–12 flashes km$^{-2}$ stretching from Tampa Bay to Cape Canaveral (Hodanish et al. 1997). During the warm season months of June–August, this flash density maximum is locally enhanced by diabatic processes and the subsequent formation of sea-breeze convergence zones, especially along the west and east coasts of the central peninsula. Not only does this central Florida maximum align with the highly populated cities of Tampa, Orlando, and Daytona Beach along Interstate 4, but the area also houses the Kennedy Space Center (KSC) and its critical daily operations.

While examining storms over central Florida, Holle et al. (1992) determined that most casualties from lightning...
occur either when the leading edge of a storm first approaches the victim, or when the back end of a storm is leaving the victim’s location. At these critical times the public is not fully aware of the threat of lightning. Therefore, forecasting for lightning initiation and cessation within thunderstorms is vital in protecting lives.

Much past research in the area of lightning forecasting has focused on the initiation of lightning, specifically CG lightning (e.g., Gremillion and Orville 1999; Vincent et al. 2003; Wolf 2006; Mosier et al. 2011). Limited research has been done on lightning cessation (e.g., Stano et al. 2010; Schultz et al. 2011), and, perhaps more importantly, on intracloud (IC) and/or total (IC + CG) lightning (e.g., Motley 2006; Clements and Orville 2008). Total lightning, by its very nature, provides a more complete inspection of the factors contributing to CG flashes. Boccippio et al. (2001a) stated that the ratio of IC to CG lightning over the continental United States is 2.64–2.94 : 1. As a result, for every one CG flash, there are nearly three IC flashes.

The addition of IC lightning in this study may provide another benefit. Most past studies have limited the use of meteorological quantities to predict only CG lightning. However, there is no apparent reason to restrict analyses to CG lightning other than perhaps because CG flash data are readily accessible. Consequently, it is advantageous to extend previous studies to include IC lightning, as certain meteorological parameters may be related to total and/or IC lightning rather than only CG lightning (MacGorman et al. 1989; Steiger et al. 2007). Monitoring of total lightning will also allow the potential use of IC flash detection as a predictor of ground-strike occurrence (Murphy et al. 2000; Weber et al. 1998) and enable diagnostic comparisons between IC and CG lightning within thunderstorms—another area that has received little attention. Finally, while CG lightning may be of most importance to ground operations, IC lightning is also of great concern to aviation, including launch operations that occur at KSC.

This study is meant to extend the work of Mosier et al. (2011), who developed automated methods to forecast CG lightning initiation using isothermal reflectivity (e.g., 40 dBZ at −10°C) and vertically integrated ice (VII) within thunderstorm cells near Houston, Texas. Isothermal reflectivity has been used by many previous studies (Buechler and Goodman 1990; Hondl and Eilts 1994; Gremillion and Orville 1999; Vincent et al. 2003; Wolf 2006) to forecast the onset of CG lightning. Although VII was developed over a decade ago by Carey and Rutledge (2000), the associated lightning forecast statistics using VII had not been closely studied until relatively recently (Gauthier et al. 2006; Motley 2006; Mosier et al. 2011). The formula for VII is as follows:

\[ VII = 1000\pi\rho_i N_0^{4/7} \left( \frac{5.28 \times 10^{-10}}{720} \right)^{4/7} \int_{H_{-10}}^{H_{-40}} Z^{4/7} dH, \]

where

- \( \rho_i \) = density of ice (917 kg m\(^{-3}\)),
- \( N_0 \) = intercept parameter (4 \( \times \) 10\(^8\) m\(^{-4}\)),
- \( Z \) = reflectivity, and
- \( H_{-10}, H_{-40} \) = height of −10°, −40°C levels (m) (−7, 11 km climatically).

Because VII is a good proxy for precipitation ice mass within a cloud, it has been found to be a useful predictor of lightning occurrence. Deierling et al. (2008) found that an increase in precipitation ice mass can lead to an increase in mean total lightning rate on the storm scale in different environments; Petersen and Rutledge (2001) found a similar linear relationship between precipitation ice water content and lightning flash density on a global scale. These results are likely due to the fact that graupel, hail, and ice crystals—all considered precipitation ice mass—are required in the most widely accepted thunderstorm charging mechanism: the noninducting charging theory (NIC; Reynolds et al. 1957; Takahashi 1978). NIC theory does not require an initial electric field but rather suggests that charge separation occurs as the result of the collision of large hail and graupel and small ice crystals in the presence of supercooled water droplets within a thunderstorm updraft.

This study will use techniques developed by Mosier et al. (2011) for a different location and will broaden their investigation to include total lightning forecasting as well as begin to examine lightning cessation. In addition to using and analyzing radar-derived lightning predictors (isothermal reflectivity and VII), we will also evaluate a third predictor of CG lightning—IC flash occurrence—in the hopes of optimizing lightning forecasting.

2. Data and methods
   a. Conventional data

Four years (2006–09) of archived level II Melbourne, Florida (KMLB), radar data from the National Climatic Data Center (NCDC) were examined for the summer (JJA) daytime hours (about 1400–0000 UTC). No subjective filtering was performed regarding volume coverage patterns (VCPs), which are used to direct elevation angles used on the Weather Surveillance Radar-1988 Doppler (WSR-88D; OFCM 2008). Although previous studies (Gauthier et al. 2006; Motley
2006) considered VCP, it is assumed that a VCP with sufficient vertical sampling was operated during the events important to this study, which mainly occurred due to severe and nonsevere convectons. This method is also consistent with Mosier et al. (2011).

The native level II KMLB radar data were converted to Universal Format (UF; Barnes, 1980) and then interpolated onto a 300 km × 300 km × 20 km Cartesian grid using the National Center for Atmospheric Research (NCAR) REORDER software package (Mohr et al. 1986; Oye and Case 1995). Both horizontal (x, y) and vertical (z) resolutions of 1 km were used in the REORDER interpolation scheme, which uses a three-dimensional Cressman interpolation scheme (Cressman 1959) with x, y, and z radii of influence of 1.25, 1.25, and 1.75 km, respectively. Although 2-km horizontal resolution is common in previous radar-based lightning forecasting studies (e.g., Gauthier et al. 2006; Mosier et al. 2011), 1-km horizontal resolution was used in this study. Sensitivity tests performed on horizontal resolution, which will be described in section 3f, indicate that a horizontal resolution of 1 km generally outperforms 2-km horizontal resolution. Vertical resolutions must balance successful differentiation between temperature levels and the creation of false features through interpolation. Mosier et al. (2011) performed sensitivity tests and determined that a 1-km vertical resolution generally performed better than 0.5-km vertical resolution over Houston. Therefore, 1-km vertical resolution was chosen for this study over Melbourne.

Morning radiosonde soundings from Cape Canaveral (XMR) were used to determine isothermal levels in the atmosphere (e.g., −10°C). Only soundings between 1000 and 1500 UTC were used in this study. These soundings usually occurred prior to convective initiation and were less likely to be contaminated by afternoon convective circulations. Afternoon soundings were also disregarded in numerous previous studies (Vincent et al. 2003; Lambert et al. 2005; Clements and Orville 2008; Stano et al. 2010).

b. Lightning data

1) NATIONAL LIGHTNING DETECTION NETWORK

CG flash data from the National Lightning Detection Network (NLDN; Cummins and Murphy 2009) were used in this study. Positive flashes with peak current less than 15 kA were omitted, following the suggestion of Biagi et al. (2007), who found that some weak positive flashes were actually IC flashes in their study. They generally concluded that the number of false CG detections equaled the number of correct CG reports at around 15 kA.

2) LIGHTNING DETECTION AND RANGING SYSTEM

The KSC Lightning Detection and Ranging (LDAR) system (Fig. 1), located on the east coast of Florida just north of Melbourne, is a three-dimensional lightning mapping system consisting of radio antennas that detect very high-frequency (VHF) emissions from lightning breakdown and channel formation processes at a frequency of about 60–66 MHz (Murphy et al. 2008). The network then uses time-of-arrival (TOA) techniques to detect the time and location of both IC flashes and components of CG flashes. The KSC LDAR-I system, which operated from the early 1990s to June 2008, consisted of six to seven VHF radio antennas, with the center latitude and longitude of the network at 28.54°N, 80.64°W. The upgraded LDAR-II system has operated since April 2008 and consists of nine new VHF radio antennas covering an area 2.5 times the width of the previous LDAR-I system (Fig. 1; Roeder 2010).

In this study spanning JJA 2006–09, VHF source data were used from both the LDAR-I and LDAR-II networks; thus, it is important to note differences between the systems. Because of the increase in the number of sensors and areal extent of the network, LDAR-II has
had an increase in detection efficiency and several other benefits over the previous LDAR-I. Subjective comparisons between LDAR systems during the summer 2007 lightning season found that LDAR-II detected about 40% more VHF sources than LDAR-I (Murphy et al. 2008). Note that a typical lightning flash produces on the order of 10 to 100 VHF sources (Murphy et al. 2008). Flash detection efficiency was at least 90% out to 90 km for LDAR-I (Boccippio et al. 2001b), whereas flash detection efficiency for LDAR-II is at least 90% out to 115 km (Murphy et al. 2008).

In LDAR-I, radial location error increased much more quickly with range than azimuthal error, producing an effect known as “radial smearing.” This error has been minimized with the LDAR-II system by virtue of its larger areal extent. Due to increased detection efficiency and the reduction in radial smearing, the LDAR-II system can provide a more detailed representation of lightning branching and even detect lightning in small new thunderstorm cells before LDAR-I (Roeder 2010). Finally, LDAR-II has eliminated the detection of electrostatic discharges from aircraft flying through precipitation clouds.

3) POSTPROCESSING

Total lightning data from LDAR and CG data from NLDN were postprocessed using two separate algorithms to attain an IC flash dataset. The first method grouped individual VHF sources from the LDAR network into flashes using specific temporal and spatial criteria. The flash-grouping algorithm developed by Murphy et al. (2000) and extended by Nelson (2002) was used in this study. Temporal criteria were as follows: a VHF source must occur within 3 s of the first observed source (the flash’s initiation point) to be included in the flash, and each source must occur within 0.5 s of the previous source in the flash. Spatial criteria involved an ellipse created around the VHF source in question using the LDAR system’s radial and azimuthal errors. This ellipse was defined by 1) a minor axis of 5000 m plus the azimuthal error (1° times the range for LDAR-I) and 2) a major axis of 5000 m plus the range error (12% of the range for LDAR-I, azimuthal error plus 10% for LDAR-II). If this ellipse contained any sources that were already grouped in the current flash, then the VHF source in question was grouped into that flash. Every flash must also contain at least three VHF sources.

Several other algorithms, listed in Stano et al. (2010), have been used in previous studies. Murphy (2006) evaluated the various flash-grouping algorithms and found that all have difficulty during high flash rates, especially events with more than 30 flashes min⁻¹. No evidence suggests that the Nelson (2002) flash-grouping algorithm performs better or worse than any other. It is important to note that radial errors, used to determine spatial constraints, were updated for the LDAR-II system, as the algorithm was originally designed for the LDAR-I system.

The second technique matched LDAR flash data with NLDN CG flash locations according to methods originally created by McNamara (2002) and used by Stano et al. (2010). Each NLDN CG flash was matched to one and only one LDAR flash, and vice versa. The results of this matching process consisted of 1) LDAR flashes considered CG and 2) LDAR flashes considered IC, which were those not correlated to an NLDN CG flash. The second array acted as the IC flash data used in this study.

c. CAPPI-SCIT algorithm and lightning correlation

Because this study was a large-scale investigation involving thousands of cells, an automated method for identifying and tracking storm cells was critical. Therefore, this study used a modified version of the Storm Cell Identification and Tracking (SCIT; Johnson et al. 1998) algorithm called Constant Altitude Plan Position Indicator (CAPPI)-SCIT. CAPPI-SCIT was developed by Mosier et al. (2011) to automate storm tracking in Cartesian coordinates rather than polar coordinates.

This study modifies the original CAPPI-SCIT algorithm to improve cell identification and tracking at distances greater than about 100 km from the radar. One of the major issues of CAPPI radar data occurs at these longer ranges, where interpolation onto the CAPPI scheme results in radar data gaps at low heights. Thus, composite reflectivity, rather than base reflectivity, was used to determine cell boundaries. This modification not only visibly improved cell identification at long ranges, but also improved the correlation of lightning data to cells.

Both CG and IC flashes were correlated to cells identified by CAPPI-SCIT. Lightning correlation was conducted radar volume by radar volume and first involved identifying all IC and CG flashes that occurred within 150 km of the KMLB radar and between the start times of consecutive radar scans (about 5 min for VCP 11). Each type of flash was then correlated to a cell by first determining if the flash (for CG, ground contact location; for IC, flash initiation point) was horizontally within a cell’s 30-dBZ composite reflectivity boundary. If this occurred, then that flash was correlated to that cell. If not, then the distance between the 30-dBZ boundaries of each cell and the flash was calculated; the flash was then correlated to the cell with the shortest distance.

An IC flash was correlated to a cell if and only if its initiation point (first detected VHF source) was within
20 km from that cell’s 30-dBZ composite reflectivity boundaries. A spatial constraint of 50 km was initially suggested in order to prevent correlation of noise (i.e., aircraft signatures) to nearby cells. The 50-km restriction was subsequently evaluated through the examination of several cases and was empirically refined to 20 km.

d. Research domain

Using the location of the KMLB radar and the center of the LDAR-I network, a radius of 100 km extending from the center of the LDAR-I network was used as the primary outer boundary of this study (Fig. 1, solid boldface line). Flash detection efficiencies for both the LDAR-I and LDAR-II systems within this range were approximately 80%–90% and above. In addition, the northernmost extent of the 100-km range lies within the range of the KMLB radar (Fig. 1, dashed line). Secondary radii of 60 and 80 km from the LDAR center location were also used in range sensitivity tests described in section 3f.

e. Predictor selection and evaluation

Radar-derived forecast predictors used in this study include both temperature level–reflectivity pairs and cell-based VII values. The standard environmental temperature levels (−10°C, −15°C, and −20°C) were calculated directly from a sounding. These environmental temperature levels have been used in several previous studies outlined in Mosier et al. (2011). The −10°C updraft level was calculated by using a sounding to determine the temperature a parcel would be in a thunderstorm updraft. This updraft level was used for comparison with both Mosier et al. (2011) and Wolf (2006). In this paper, updraft temperature levels are indicated as such; if a temperature (e.g., −15°C) is not labeled, then it is an environmental temperature level.

Because our goal was to optimize lightning forecast predictors, reflectivity values used in this study ranged from 5 to 60 dBZ to ensure that all possible predictors were included. Sensitivity tests (described in section 3f) were performed on range from the LDAR network center (60 and 80 km versus 100 km) and track count, or the number of radar volumes the cell was tracked by the CAPPI-SCIT algorithm. For example, if a cell was identified on one radar volume and then tracked for two additional scans, then a track count of two would be used. Cell-based VII forecasts of lightning were also performed in a similar manner to those in Mosier et al. (2011). This entailed calculating the distribution of VII values throughout the entire dataset and using the resulting percentiles at both CG and IC occurrence (increments of 5%) as forecast criteria (Table 1). IC flashes were also used as an additional predictor of CG lightning.

A summary of the methods used to create a cell-based forecast of IC and CG lightning is given here. These steps are modeled after techniques used by Mosier et al. (2011). The summary is as follows: 1) CAPPI-SCIT was processed on all radar volumes occurring within the determined time ranges to identify and track cells; 2) the environmental temperature and updraft levels were calculated from the XMR sounding; 3) for each cell in the radar volume, the reflectivity levels were determined at the environmental and updraft levels; 4) for each cell, if the reflectivity reached the predetermined thresholds, then a “yes” forecast was made; 5) for each cell, if the VII reached the predetermined percentiles, then a yes forecast was made; and 6) for each cell, if an IC flash occurred, then a yes forecast was made.

Two methods were used to measure the skill of each radar-based forecast predictor. The first method involved using statistical measures—probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) [see Gremillion and Orville (1999) and Wilks (1995) for definitions]—to measure each predictor’s accuracy and reliability. POD is the probability that an event would be forecast, given that it occurred. FAR is the fraction of forecast events that turn out to have occurred. The CSI is the ratio of the number of

### Table 1. VII percentiles (kg m⁻²) at CG and IC occurrence and nonoccurrence across the entire dataset.

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<th>VII at 0000</th>
<th>VII at IC</th>
<th>VII at 0000</th>
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correctly forecasted events to the sum of the total number of predicted events plus the incorrectly predicted non-events. The second method involved using lead times between the time of forecast and the first occurrence of lightning in each cell. This study calculated lead time for the radar-derived predictors by using the difference between the start time of the radar scan during which the forecast was made and the time of the first IC flash and first CG flash. This calculation is consistent with previous studies (Gremillion and Orville 1999; Clements and Orville 2008; Mosier et al. 2011). However, it is important to note that the actual operational lead time of each forecast is much shorter, consisting of both the radar scan time and algorithm processing time. Therefore, lead times in this study should not be used operationally; here, they are used strictly for comparison and evaluation of forecasts, both within this study and to similar past studies.

3. Results

a. Initiation and cessation comparisons by flash type

Figure 2 shows a Venn diagram summarizing cell occurrence at a range of 100 km or less from the LDAR network and spanning from the summer months of 2006 through 2009. Out of 17 649 total cells, 39% contained lightning (at least one flash). Of the cells with lightning, 60% contained both CG and IC flashes. Interestingly, over 700 cells (4% of total cells, 10% of cells with lightning) produced only CG flashes, which may be higher than initially hypothesized.

Every cell with both types of lightning was analyzed to determine the time of initiation and cessation of each flash type (Table 2). More than three-quarters of all cells produced an IC flash first and almost two-thirds of all cells produced an IC flash as the last flash. In contrast, CG lightning was last in about 36% of all cells, which is consistent with the 30% found by Clements and Orville (2008) in their analysis of 37 ordinary thunderstorms over Houston. These percentages support the theory that lightning in thunderstorm cells evolves as follows: 1) IC initiation, 2) CG initiation, 3) CG cessation, and 4) IC cessation (Williams et al. 1989).

The first IC flash provided at least a 10-min warning time before the first CG flash in about 10% of cells [not shown; consistent with Murphy et al. (2000)]. In about 30% of the cells, the first CG flash preceded the first IC flash. Similar percentages were found for cessation.

VII was calculated at each radar scan coinciding with each type of lightning initiation and cessation (Fig. 4). Several features are evident: 1) VII at the time of CG initiation is significantly higher than VII at CG cessation, 2) VII at the time of IC initiation is significantly higher than VII at IC cessation, 3) VII at the time of CG initiation is somewhat higher than VII at the time of IC initiation, and 4) VII at CG cessation is slightly higher than VII at IC cessation.
The Kruskal–Wallis test, a comparison of medians, was performed on each of these differences to test the statistical significance of each. The first three differences are statistically significant while the last difference, between VII at CG cessation and VII at IC cessation, has a $p$ value greater than our significance level of 0.001. We would likely need a larger sample size to determine if this difference is statistically significant.

The first two features listed above (VII higher at initiation than at cessation) support the theory that a comparatively large amount of ice mass is needed for a storm in its developmental stage to produce adequate charge separation and thus lightning. Once sufficient charge separation has occurred, however, it is possible that lightning can continue to strike, even if VII has decreased during storm dissipation. The final two features (VII somewhat higher at CG occurrence than at IC occurrence) provide evidence that IC flashes can occur in storms with lower VII. In contrast, CG flashes may more likely occur in storms with cloud bases near the ground, which could increase the storm’s vertical depth and thus VII.

b. Radar reflectivity method

All statistics and lead times discussed in the sections below involve cells within 100 km of the LDAR network center and with a minimum track count of zero (i.e., the cell was identified in one radar volume scan by the CAPPI-SCIT algorithm, but may or may not have been tracked in subsequent radar volume scans). Sensitivity tests concerning range and track count and their effects on resulting statistics and lead times will be discussed in section 3f.

To determine the best radar reflectivity predictor of CG lightning initiation within our 4-yr database, POD, FAR, and CSI were computed for each pairing of reflectivity value and isothermal level. The five best reflectivity values were chosen according to highest CSI, and statistics for each pairing were plotted. Figure 5 (top) shows CSIs for the five best reflectivity predictors of CG lightning: 20, 25, 30, 35, and 40 dBZ, at the environmental $-10^\circ$, $-15^\circ$, and $-20^\circ$C levels and updraft $-10^\circ$C level—labeled E10, E15, E20, and U10, respectively. Overall, the predictor of CG lightning with the highest CSI was 25 dBZ at $-20^\circ$C (CSI of 0.47). This predictor balanced comparatively high POD (0.78) with lower FAR (0.46).

Gremillion and Orville (1999) found 40 dBZ at $-10^\circ$C to be the best predictor of CG lightning initiation over the Kennedy Space Center, but they required their criteria to be met for at least two consecutive scans. Wolf (2006) found the best CG predictor over Jacksonville, Florida, to be 40 dBZ at the updraft $-10^\circ$C level. Mosier et al. (2011) found 30 dBZ at $-20^\circ$C to be the best CG initiation predictor over Houston. It is important to note that differences in “best” lightning predictors may result from differences in kinematic properties (e.g., updraft strength) and thus microphysical properties and structure of storm clouds from location to location.
The same analysis was performed for IC lightning initiation prediction. Figure 5 (bottom) shows CSI for the six best reflectivity predictors of IC lightning at the environmental $-10^\circ$, $-15^\circ$, and $-20^\circ$ C levels and updraft $-10^\circ$ C level—labeled E10, E15, E20, and U10, respectively.

The same statistics (not shown) were calculated for total lightning prediction (i.e., predicting either an IC or CG flash to occur). It was found that, in general, CSI was higher for total lightning prediction than for just CG or IC lightning, mainly due to the significantly lower FAR for each predictor. The best predictors of total lightning, according to CSI, were 20 dBZ at $-15^\circ$ C and 25 dBZ at $-10^\circ$ C (CSI, 0.64; FAR, 0.34; POD, 0.96; for both). Consequently, when predicting total lightning, a forecaster should generally look for lower reflectivities at lower reflectivity values at equivalent isothermal heights) produces more IC than CG flashes.

Fig. 5. CSI for the (a) five best reflectivity predictors of CG lightning and (b) six best reflectivity predictors of IC lightning at the environmental $-10^\circ$, $-15^\circ$, and $-20^\circ$ C levels and updraft $-10^\circ$ C level—labeled E10, E15, E20, and U10, respectively.
lower heights within a storm cloud, in comparison to forecasting for only IC or only CG lightning.

A second technique for analyzing the utility of radar-derived forecast predictors was to calculate the lead time from each predictor to the occurrence of CG and IC lightning (Fig. 6). The best lead time for CG predictors with track counts of zero and within 100 km was 8.5 min using 20 dBZ at −10°C. Mosier et al. (2011) found a comparable lead time of about 8 min when using 30 dBZ at −10°C with a track count of zero. The best lead time was 7 min for IC lightning using 5 dBZ at −10°C. In general, lead times for IC predictors were lower than lead times for CG predictors by more than a minute, which is consistent with the tendency of IC flashes to occur earlier in a storm. The best CG predictor according to highest CSI—25 dBZ at −20°C—had an average lead time of about 6.4 min, whereas the best IC predictor—25 dBZ at −15°C—had an average lead time of about 6.1 min. Therefore, using the best (highest CSI) CG predictor provides a slightly longer lead time than using the best IC predictor.

c. VII percentile method

Vertically integrated ice percentiles at both CG and IC occurrence across the entire dataset were used as the forecast predictors of the VII method (Table 1). Note
that percentiles at IC occurrence are consistently lower than those at CG occurrence, which is consistent with conclusions drawn from Fig. 4. VII percentiles were also calculated at CG and IC nonoccurrence (radar volume scans without the occurrence of a CG or IC flash; Table 1). VII values at both CG and IC nonoccurrence are essentially zero until the 90th percentile.

Figure 7 illustrates the CSI for each VII percentile predictor of CG and IC lightning initiation. Note that VII CG percentiles were used for CG lightning prediction, while VII IC percentiles were used for IC lightning prediction. CSI is higher for IC prediction than for CG prediction for the majority of percentiles. The best VII predictor of CG lightning was the 30th percentile (0.840 kg m$^{-2}$), with a CSI of 0.47. Mosier et al. (2011) found the best VII predictor of CG lightning to be between 0.42 and 0.58 kg m$^{-2}$ for their study. The best VII predictor of IC was the 5th percentile (0.143 kg m$^{-2}$), with a CSI of 0.58. Thus, the best VII predictor of CG lightning is nearly 6 times higher than the best VII predictor for IC lightning. This may be due to the apparent requirement of higher VII for CG flash initiation as compared to IC initiation. In addition, CSI values using VII as a predictor for lightning yield results that are generally similar to those found when using the radar reflectivity method.

Figure 8 displays the lead times for both CG and IC lightning using the VII forecast method. The best lead time was 8.6 min for CG lightning at the 0th percentile (i.e., VII $> 0$ kg m$^{-2}$) and 7 min for IC lightning at the 0th percentile. Lead time for CG lightning was consistently higher than lead time for IC lightning due to higher VII values required for CG initiation. The best VII percentile predictor of CG according to CSI—30th percentile—had an average lead time of 6.1 min, while the best VII percentile predictor of IC—5th percentile—had an average lead time of 6.7 min. Once again, lead times using VII as a predictor for lightning are generally similar to using a radar reflectivity threshold.

d. IC as predictor of CG

The last predictor of lightning used and analyzed involved employing the first IC flash as a predictor of the first CG flash. Forecast verification statistics for this predictor were calculated in a similar fashion. When comparing CSI to that of the other two best predictors of CG lightning initiation—25 dBZ at $-20^\circ$C and VII 30th percentile—this method outperforms both (Table 3). CSI for IC as a predictor of CG was 0.55, whereas CSI for the other two best predictors of CG was 0.47. Furthermore, FAR was lower than both (0.35 versus 0.46 and 0.44, respectively) and POD was equal to or higher (0.78 versus 0.78 and 0.75, respectively).

Average lead time was 2.4 min when using the first IC flash as a predictor of CG lightning. Although this lead time is significantly lower than the other two best predictors of CG (6.4 and 6.1 min), no algorithm processing or radar scan times are required. Thus, actual lead times may be much more comparable when taking into account automation processing times.

e. Predictor summary

A useful way of displaying a summary of forecast statistics is through a contour plot of CSI as a function of

![CSI: VII percentiles](image-url)
FAR and POD (Fig. 9; Gerapetritis and Pelissier 2004). Data from the various predictors of CG (black) and IC (gray) lightning are overlaid: isothermal reflectivity (circles), VII percentiles (plus signs), and IC as a predictor of CG (asterisk). Note that the lowest reflectivity value (5, 10, and 15 dBZ) levels and VII percentiles (5th, 10th, and 15th percentiles) have the highest PODs and are thus located near the top of Fig. 9. However, these predictors also have higher FARs than most predictors.

Figure 9 reinforces the idea that VII predictors of both CG and IC lightning have generally similar statistics when compared to the radar reflectivity method. It is also evident from this contour plot that using the first IC flash as a predictor of CG initiation provides a significantly higher CSI value than any of the radar reflectivity predictors of CG initiation.

f. Sensitivity to horizontal resolution, range, and track count

Many past radar analysis studies have used CAPPI radar data with 2-km horizontal resolution (e.g., Gauthier et al. 2006; Mosier et al. 2011). A cursory examination of 1- versus 2-km horizontal resolution in radar data was performed on a short case during June 2007, as it demonstrated typical scattered convection common over east-central Florida in the summer. It was found that the CAPPI-SCIT algorithm correctly identified two cells in close proximity as two separate cells in the 1-km resolution data, whereas the cells were often identified as one large cell in the 2-km resolution radar data. Therefore, it is suggested that when working with cell identification and tracking algorithms, CAPPI radar data with 1-km horizontal resolution should be used, as it likely outperforms coarser-resolution data. However, it is possible that horizontal interpolation resulting from higher-resolution radar data (1 km) may create spurious features at long distances from the radar.

Sensitivity tests (not shown) were also performed comparing both range from the LDAR network center (60, 80, and 100 km) and track count (0, 1, and 2). Lead time was found to be highest for cells with a track count of at least two radar volumes within 100 km; the average lead time for predicting CG (IC) in these cells was on the order of 9–11 (7–9) min for predictors between 20 and 30 dBZ at between −10° and −15°C. Similar lead times of 9–11 (7–9) min were found for track counts of two within 100 km for VII predictors of CG (IC) between the 5th and 30th percentiles. These lead times of about 11 min for cells with a track count of two within 100 km of the LDAR network were the highest lead times found in this study.

Comparisons of statistics for radar threshold and VII predictors, with regard to range and track count, produced the following results:

<table>
<thead>
<tr>
<th>Type</th>
<th>POD</th>
<th>FAR</th>
<th>CSI</th>
<th>Lead time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC</td>
<td>0.78</td>
<td>0.35</td>
<td>0.55</td>
<td>2.4</td>
</tr>
<tr>
<td>25 dBZ at −20°C</td>
<td>0.78</td>
<td>0.46</td>
<td>0.47</td>
<td>6.4</td>
</tr>
<tr>
<td>VII 30th percentile</td>
<td>0.75</td>
<td>0.44</td>
<td>0.47</td>
<td>6.1</td>
</tr>
</tbody>
</table>

**Table 3.** Statistics (POD, FAR, CSI) and lead times (min) for the best predictors of CG flashes, including IC as a predictor of CG.
POD was slightly higher (on the order of $0.01$) for track count 2 versus 0; POD was slightly higher ($0.01$) for 100 versus 60 km. FAR was lower ($0.1$) for track count 2 versus 0, was slightly lower ($0.01$) for CG 100 versus 60 km, and was slightly lower ($0.01$) for IC 60 versus 100 km. CSI was higher ($0.1$) for track count 2 versus 0 and was generally the same for range. Therefore, it is determined that, in general, differences in track count provide greater improvement in forecast statistics, especially CSI, as compared to differences in range, which is consistent with Mosier et al. (2011).

Not surprisingly, the highest CSI and POD and lowest FAR for IC as a predictor of CG was found for cells with a track count of two within 60 km (CSI, 0.63; FAR, 0.27; POD, 0.81). Higher LDAR flash detection efficiencies occur at shorter ranges (less than 60 km), most likely resulting in better forecast statistics for using IC lightning as a predictor of CG occurrence.

g. Interannual variation

Because this study spanned four summer seasons, the interannual variation of lightning counts was investigated. Monthly counts of CG and IC flashes within 100 and 60 km of the LDAR networks were totaled, and the relative proportion of intracloud to cloud-to-ground lightning (IC:CG ratio) was calculated (Fig. 10). Average IC:CG ratio (100-km range) for the whole period was 2.65, which is consistent with Boccippio et al. (2001a), who found a ratio of between 2 and 2.5 over central portions of the Florida Peninsula. Coincidentally, their analysis found a continental mean IC:CG ratio of 2.64. Differences between this study’s calculation of IC:CG and that calculated by Boccippio et al. (2001a) may be primarily due to differences between IC lightning detection techniques. Boccippio et al. (2001a) used satellite-based optical detection of IC lightning from the Optical Transient Detector (OTD), while this study used ground-based VHF detection of IC lightning from the LDAR system.

A general increase in IC:CG ratio is evident at both ranges, due to overall higher IC counts and relatively constant CG counts beginning in July 2007. Because an increase in IC counts from 2006–09 is still apparent at $\leq 60$ km, the increase in flash detection efficiency from the LDAR-I to LDAR-II systems, especially at longer ranges, is not likely a large factor.

Natural variability may be a factor in explaining observed changes in lightning counts. Precipitation totals from observational rain gauges, however, showed no apparent trend over Melbourne from JJA 2006 to JJA 2009. Precipitation over the area of study was significantly higher during August 2008 due to Tropical Storm Fay providing upward of 50 cm of rain to east-central Florida. Nevertheless, trends in rainfall may not necessarily indicate trends in lightning. Tropical storms and stratiform systems may increase rainfall totals but not necessarily increase lightning totals. Lyons and Keen (1994) found an absence of CG lightning within the interior of tropical storms. Seliga et al. (2002) state that low vertical velocities and microphysical properties not conducive to lightning production dominate stratiform precipitation. Differences in synoptic weather patterns, such as prevailing wind direction and thus direction of the sea breeze, may play a key role in the variation of precipitation as well as changes in lightning totals from month to month and year to year.

4. Conclusions

This research is distinct from other past lightning forecasting studies in several ways. First, through the use of automation, we have been able to analyze more than 17 000 individual convective cells collected over the east-central Florida region—more than 300 times as many cells as numerous prior studies. By investigating such a large number of storms, we were able to arrive at statistically significant results. Second, this study examines total lightning in the hopes of optimizing both IC and CG
flash forecasting—something that has not been pursued in detail. Finally, while many previous studies have focused on CG lightning initiation, we have presented diagnostic comparisons between initiation and cessation for both CG and IC flash types.

While the great majority of storms with lightning (nearly 90%) contained at least one IC flash, still over 700 cells (4%) contained only CG lightning. Further analysis would be useful in gaining insight into why these storms produced only CG flashes. An analysis of the IC:CG ratio over our database showed numbers consistent with previous studies concerning this ratio: 2.64, although month-to-month and year-to-year variability was evident.

The VII at CG and IC initiation was higher than at CG and IC cessation. Because VII is a proxy for ice mass accumulation in a storm, this result supports the hypothesis that a large amount of ice mass buildup is necessary for a storm to produce charge separation and thus lightning at initiation. Once sufficient charge separation has occurred, however, it is possible that lightning can continue to strike, even if VII has lowered during storm dissipation.

The best reflectivity threshold predictors of CG and IC lightning initiation for this study, according to highest CSI, were 25 dBZ at −20°C and 25 dBZ at −15°C, respectively. Meanwhile, the best VII predictor of CG lightning initiation was the 30th percentile (0.840 kg m⁻²), and the best VII predictor of IC was the 5th percentile (0.143 kg m⁻²), or nearly 6 times lower than for CG lightning. CSIs for both reflectivity and VII methods were also found to be higher overall for IC forecasts than for CG forecasts. However, lead times were consistently lower for IC lightning due to the tendency of IC lightning to occur earlier in a storm. Nevertheless, using the best (highest CSI)

![Figure 10. Monthly IC:CG ratio: lightning (top) within a range of 100 km from the LDAR network and (bottom) within 60 km.](image-url)
VII predictor for IC prediction provides a slightly longer lead time (6.7 min) than using the best (highest CSI) VII predictor for CG prediction (6.1 min).

The VII predictors used in this study had similar statistics and lead times when compared to the radar reflectivity method. Furthermore, VII is a fairly straightforward algorithm to produce from WSR-88D data, so future use of VII as an operational predictor of total lightning shows promise.

VII was found to be lower at IC occurrence, including at initiation, than at CG occurrence, providing evidence that intracloud flashes can occur in storms with lower vertically integrated ice and, thus, lower overall charge separation. One possible reason could be that IC flashes occur in storms with less vertical depth and thus less vertically integrated ice.

In our general database overview of cells, we found that 76% of cells had IC initiation before CG initiation, while 63% of cells had IC cessation last. Clements and Orville (2008) stated that using total lightning VHF sources provides little utility in CG forecasting—only about a 3-min warning time. However, studies have empirically shown the utility of IC as a warning indicator of CG flashes (Weber et al. 1998; Murphy et al. 2000). When we looked more closely at our data, we found that, in fact, using the first IC flash as a predictor of CG occurrence statistically outperforms other predictors of CG lightning. CSI for this method (0.55) was higher than CSI for both the best reflectivity threshold method and the best VII percentile method (0.47) (each with a track count of zero within 100 km). Furthermore, when considering only those cells with a track count of two and within 60 km of the LDAR network, IC as a predictor of CG still outperformed the other predictors of CG (CSI of 0.63 versus 0.53 and 0.51). Even though the average lead time for using IC as a predictor of CG was only 2.4 min, when taking into account automation processing and radar scan time for the other two methods, lead times are much more comparable. Furthermore, IC as a predictor of CG could be the most useful method for the general public, as almost anyone outside can spot an IC flash or hear the thunder associated with an IC flash in a storm and take the necessary safety precautions. While the reflectivity threshold and VII percentile methods could be useful for the experienced forecaster, using the first IC flash could turn out to provide the simplest and most practical method for predicting CG lightning initiation.

Synoptic weather patterns, such as prevailing wind direction and sea-breeze formation, may play a key role in the interannual variation of lightning as well as precipitation within this study. Future work focusing on different synoptic weather blueprints and the resulting precipitation and lightning will provide climatological insights into the general long-term patterns of severe storm formation and dissipation over Florida.

Future work should also address using similar approaches in forecasting the cessation of lightning within storms. Although this study provided a cursory glance into this issue, more research is necessary to more accurately predict when the last flash occurs in a storm. Methods like maximum time interval between flashes used in Stano et al. (2010) should be investigated. In addition, the utility of VII, which has continued to show potential, should be examined not only for forecasting initiation and cessation, but also for predicting the probability of a certain CG or IC flash rate within storms. Finally, polarimetric radar, which should be operational in the United States in the near future, will provide further insights into mixed-phase composition within storm clouds and thus proxies for charge separation and lightning formation and dissipation.

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