USING WSR-88D REFLECTIVITY DATA FOR THE PREDICTION OF CLOUD-TO-GROUND LIGHTNING: A CENTRAL NORTH CAROLINA STUDY

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Abstract

Charge separation most likely occurs during rebounding collisions between ice crystals and large ice hydrometeors (such as graupel and hail) that remain suspended in the mixed phase zone by the updraft of a growing thunderstorm. The WSR-88D reflectivity data can be used to indirectly identify this electrification process within a growing thunderstorm because graupel and hail return large reflectivity echoes. This study examined a sample of 50 central North Carolina thunderstorm cases using three different characteristics of WSR-88D data (i.e., reflectivity threshold [dBZ] at a given environmental temperature [° C] for a specified number of volume scans [# Vol]) that were organized into eight different sets of criteria for judging the cloud-to-ground (CG) lightning potential. Preliminary results showed that the best lightning prediction algorithm was associated with either the 1 Vol / 40 dBZ / –10° C or 1 Vol / 40 dBZ / –15° C criteria. Based on the critical success index (CSI), the 1 Vol / 40 dBZ / –10° C criteria did the best with a 63% CSI, 100% probability of detection (POD), and a 37% false alarm rate (FAR). The 1 Vol / 40 dBZ / –15° C criteria closely followed with a 62.5% CSI, 86% POD, and a 30% FAR. Lead times for these criteria were 14.7 minutes and 11.0 minutes, respectively. If lead time is a high priority and a slight reduction in CSI can be tolerated, the 35 dBZ criterion may be a better choice. The 35 dBZ criterion resulted in lead times 2-3 minutes longer than with 40 dBZ. Overall, the results obtained in this study compared very well with results obtained in past studies. In addition, an analysis of vertical reflectivity lapse rates between the 0° C and –20° C isotherm heights in both detection and false alarm cases showed that vertical reflectivity lapse rates for false alarms (–2.04 dBZ / kft) were much larger than for detections (–0.69 dBZ / kft). The results show that it is possible to use WSR-88D reflectivity data to reasonably predict the onset of CG lightning in the central North Carolina region using criteria similar to that used in previous studies of thunderstorms in other regions.

1. Introduction

Forecasting the initiation of lightning activity is important for the protection of human life and property. Cloud-to-ground (CG) lightning strikes are the second leading cause of convective weather related deaths in the United States, with an average of 87 deaths per year reported (Curran et al. 2000). From 1959 to 1994, North Carolina ranked second for fatalities and fourth for injuries, casualties, and damage due to lightning strikes in the United States (Curran et al. 2000). CG lightning strikes can be detected in real-time using the National Lightning Detection Network (NLDN), which is commercially owned and operated by Vaisala Inc. The NLDN is comprised of more than 100 antenna stations that are connected to a central processor that records the time, polarity, signal strength, and number of strokes of each CG flash detected. Depending on the location within the network, Vaisala Inc. estimates an average location accuracy of within 500 meters, with a detection probability between 80-90 percent, varying slightly by region (Cummins et al. 1998).

Originally, forecasting lightning was synonymous with the forecasting of convection (i.e., every convective cell was assumed to have the potential for producing lightning). Shortly after the introduction of weather radar, Workman and Reynolds (1949) concluded that the onset of significant electrification was associated with the rapid vertical development of convection and the presence of precipitation ice in a mixed phase environment (i.e., presence of small ice crystals and supercooled cloud water) at about the height of the -10°C isotherm. Based on these results, Reynolds and Brook (1956) noted the near coincidence of radar detectable precipitation and significant cloud electrification around T = -10°C, especially when the precipitation echo exhibited rapid vertical development. Shackford (1960) showed that lightning stroke rate was related to radar reflectivity maxima above the 0°C level and to vertical profiles of reflectivity. Building on these early results, Larsen and Stansbury (1974) and Marshall and Radhakant (1978) demonstrated that the area of moderate (> 30 - 43 dBZ) radar reflectivity echo at heights from six to seven km were closely associated with

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the location, timing, and frequency of lightning. In effect, radar based maps of the "Larsen Area" were effective as lightning indicators. Detailed radar and in-situ studies of cloud electrification and lightning during the 1980's and 1990's (e.g., Dye et al. 1986, 1989; Goodman et al. 1988; Williams et al. 1989; Carey and Rutledge 1996, 2000; Ramachandran et al. 1996) demonstrated a conclusive relationship between the presence of graupel in a mixed phase environment and subsequent cloud electrification and lightning. The interested reader is referred to MacGorman and Rust (1998) for a detailed review of these and many other field studies. These experiments confirmed that the first appearance of moderate reflectivity (30 – 40 dBZ) at temperatures between about –10°C and –20°C preceded the first CG lightning flash by five to thirty minutes (e.g., Dye et al. 1989; Michimoto 1990). After the widespread introduction of the WSR-88D in the late 1980s and early 1990s, applied research and operational use of this knowledge showed that CG lightning strikes occurred soon (4 – 45 minutes) after certain WSR-88D reflectivity values (10 – 40 dBZ) were reached at various isothermal (0°C, –10°C, –15°C, and –20°C) levels within a thunderstorm (e.g., Buechler and Goodman 1990; Hondl and Eilts 1994; Gremillion and Orville 1999).

It is important to understand the basic principles of electrification in thunderstorms in order to understand why WSR-88D data can be used to predict the onset of CG lightning. A typical thunderstorm has updrafts on the order of 10 m s^{-1}. These strong updrafts loft cloud liquid water droplets above the environmental freezing level where they become supercooled. Supercooled water droplets will homogeneously nucleate at temperatures of –40°C or less, but will nucleate at much warmer temperatures if a catalyst is present. It has been observed that supercooled water droplets first begin to nucleate on insoluble aerosols (soil mineral, volcanic ash, etc.) at temperatures of about –10°C (e.g., Young 1993). After supercooled water droplets nucleate, the resultant ice particles begin to grow into ice crystals through deposition. As the ice crystals grow in the thunderstorm, some grow slower than others. Smaller ice crystals, along with ice splinters and fragments are lofted high into the upper levels of the storm. Larger ice crystals grow within the updraft at midlevels where ice supersaturation is greatest. As the large ice crystals grow by deposition and aggregation, they gain more mass and begin to descend with respect to smaller supercooled water droplets. In the process of descending, large ice crystals rime with supercooled droplets and eventually gain enough mass to fall through the updraft as graupel or hail. Graupel and hail may also form initially from the freezing of millimeter-sized raindrops. When in the presence of supercooled water, the collision of graupel and small upward moving ice crystals results in a charge separation. This charge separation process is known as the ice-ice collisional (or non-inductive) charging mechanism (e.g., Takahashi 1978).

For typical conditions (i.e., liquid water contents on the order of 1 g m^{-3} and temperatures between –10°C and –30°C), a positive charge is acquired by the small ice crystals that are lofted into the upper levels of the storm and a negative charge is acquired by the larger ice crystals and graupel that are suspended by the updraft in the midlevels of the storm. Consequently, except for convective cells associated with only warm rain, the first radar echo greater than 35 dBZ in the growing thunderstorm is observed between the –10°C and –20°C temperature level where graupel is suspended and growing in the updraft. In humid (e.g., tropical) environments where the first radar echo occurs at temperatures greater than 0°C, vigorous convection can loft millimeter-sized drops above the height of the 0°C isotherm. These supercooled raindrops freeze around temperatures of –10°C and become an instant hailstone or frozen drop. Thus, the appearance of a 30-40 dBZ or greater radar echo between –10°C and –20°C indicates the possible presence of a sufficient quantity of graupel or hail suspended in an updraft with ice crystals and supercooled water for charging, and ultimately, lightning.

The motivation for this study stems from the inexact relationship between radar reflectivity and the necessary ingredients for electrification and lightning (e.g., graupel, ice crystals, and supercooled water). Although there are several previous studies on using WSR-88D reflectivity data to predict the onset of CG lightning, this inexact relationship could result in regional variability in the behavior of the lightning prediction criteria. In addition to exploring the behavior of different lightning prediction criteria in central North Carolina, the authors also wish to explore ways to improve the results (e.g., by examining vertical reflectivity lapse rates). This paper examines a sample of 50 central North Carolina thunderstorm cases that were collected and then analyzed using eight different sets of WSR-88D reflectivity criteria.

2. Data/Methodology

The sample in this study consists of 50 cases taken from 13 lightning days (Table 1). Of those 50 cases, 24 cases were recorded in real time at the National Weather Service Forecast Office in Raleigh, North Carolina, and the remaining 26 cases were post analyzed using archived NLDN and Level II radar data at North Carolina State University. In addition to the before-mentioned cases and case days, nine additional cases from

Table 1. All lightning days, the total number of cases each lightning day, and the number of those cases that were post analyzed.

Lightning Day (mm/dd/yy)	# Total Cases (# Post Analyzed)
9/9/01	1(0)
9/20/01	1(0)
9/21/01	2(0)
3/17/02	1(0)
3/26/02	3(2)
3/30/02	2(0)
4/14/02	6(5)
4/15/02	11(9)
4/19/02	7(4)
5/30/02	10(6)
5/31/02	1(0)
6/5/02	2(0)
6/26/02	3(0)

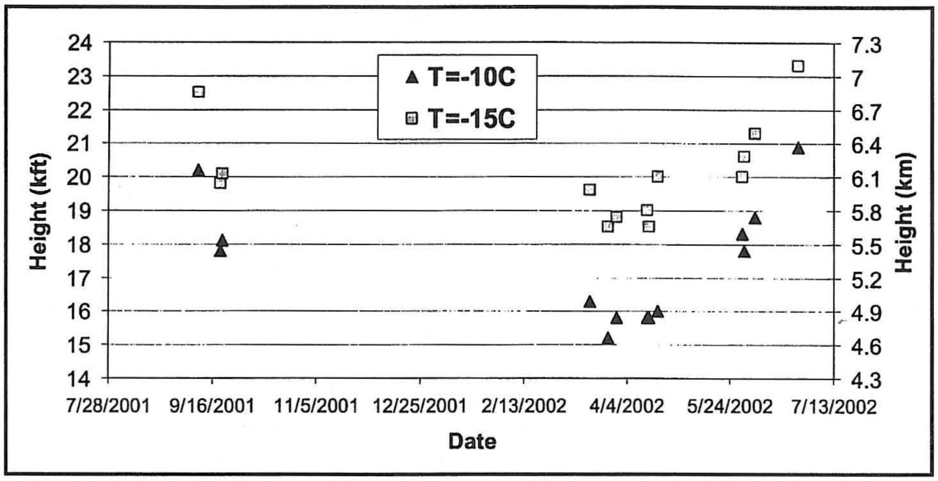

Fig. 1. Time series of the heights (kft [left] and km [right]) of the -10°C (triangles) and -15°C (squares) temperature levels for each case study day during the study period.

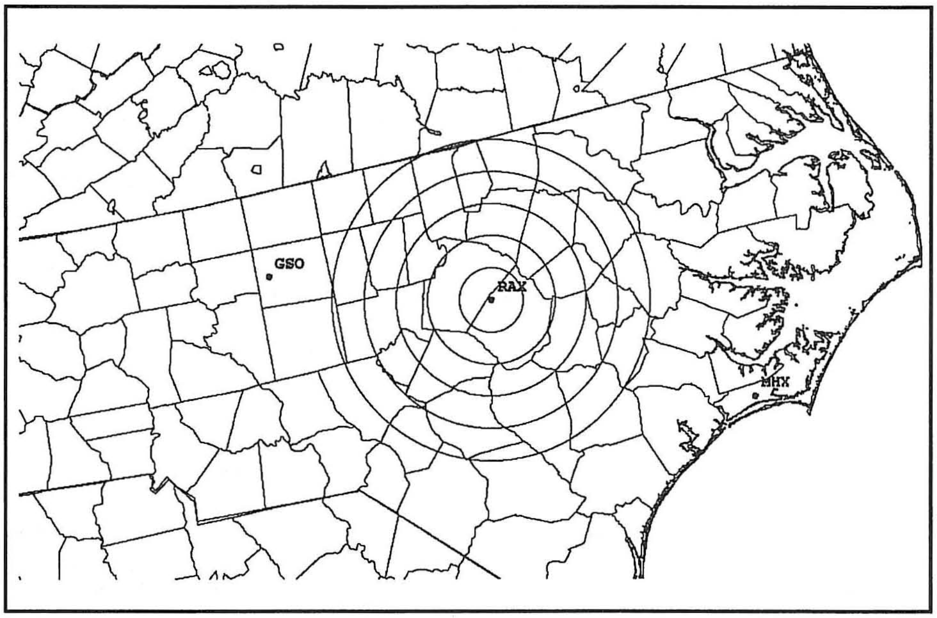

Fig. 2. Map of study domain. The WSR-88D location (RAX) is shown with range rings at 20 km increments out to 100 km. The two upper-air stations used in the study (Greensboro, North Carolina [GSO] and Morehead City, North Carolina [MHX]) are also shown.

Table 2. Different sets of criteria that were used in the study

Criteria Set #	# Volume Scans	Z-Threshold (dBZ)	Environ. Temp. (°C)
1	1	35	–10°C
2	1	35	–15°C
3	1	40	–10°C
4	1	40	–15°C
5	2	35	–10°C
6	2	35	–15°C
7	2	40	–10°C
8	2	40	–15°C

17, 27, 28 and 29 August 2001 were included so that late summer (July-August) pulse-type thunderstorms could be examined as well. These cases and case days were not included in the main sample because they were examined in real time only at the height of the –10°C isotherm. Late summer cases for 2002 were unavailable due to drought conditions over central North Carolina during this time.

For post analysis at NCSU, archived Level II radar data for KRAX (Raleigh, North Carolina) were obtained via NOAA/National Climatic Data Center (NCDC) for the following days in 2002: 26 March, 14-15 April, 19 April, and 30 May. NLDN lightning data for the continental U.S. were obtained for the same days. Archived model data, surface observations and upper-air soundings were also obtained.

Eight sets of criteria were used in analyzing the recorded convective cells. The criteria were comprised of the following three variables: the number of radar volume scans, the minimum reflectivity and the height of the –10°C or –15°C isotherm (Table 2). Criteria 1-4 hold the number of volume scans constant at one while varying the Z-threshold (35 or 40 dBZ) and environmental temperature (–10°C or –15°C), while criteria 5-8 hold the number of volume scans constant at two while varying the Z-threshold (35 or 40 dBZ) and environmental temperature (–10°C or –15°C).

The height of the –10°C and –15°C isotherms were an average between those recorded from the 1200 UTC GSO (Greensboro, North Carolina) and MHX (Morehead City, North Carolina) soundings for each case day. If one particular sounding was clearly more representative of the atmosphere over the central North Carolina region, the heights from that sounding were used exclusively. Time series of the heights of both environmental temperatures (i.e., -10°C and -15°C) for each case day during the study are presented in Fig. 1. As expected, there is a seasonal trend in the heights of the two temperature levels. For the period studied herein, there is a clear tendency in the heights of the -10°C (-15°C) temperature level to increase from a minimum of about 15-16 kft (18-20 kft) in late March and early April to a maximum of about 20-21 kft (23-24 kft) in late June to early July. As a result, the heights varied by as much as 6 kft (1.8 km), or approximately 30% during the study period. Day-to-day variability of the heights was as much as 1-1.5 kft (0.3-0.5 km). The average and standard deviation of the –10° C and –15°C isotherm heights for all case days used in the study are included in Table 3. A domain map of where this study took place, along with the location of the radar and upper-air sounding stations utilized is shown in Fig. 2.

Table 3. Average and standard deviation of the heights (kft) of the –10°C and –15°C isotherms.

Avg. Height of the -10°C Isotherm (kft)	Standard Deviation of the -10°C Isotherm (kft)	Avg. Height of the -15°C Isotherm (kft)	Standard Deviation of the -15°C Isotherm (kft)
17.4	1.8	20.2	1.5

It is important to note that even though the ice particle temperature is what controls the extent and timing of electrification (e.g., Takahashi 1978), the environmental temperature is used in this study as a simplification. This simplification is justified because there is enough uncertainty regarding the required in-cloud temperature for significant charging and the estimation of the in-cloud temperature such that a more complex procedure is not warranted. In addition, the procedure must be straightforward to apply in a real-time, operational context.

Convective cells were recorded at the NWS Forecast Office in Raleigh by following a few procedures. First, a 4-panel PPI display of the lowest four elevation angle radar scans was loaded in the Advanced Weather Interactive Processing System (AWIPS). Second, by right clicking on one of the PPI displays and selecting "sampling", a readout of reflectivity, height (in msl and agl), and azimuth/range from the radar was used to determine the reflectivities of a convective cell at the heights of the –10°C and –15°C isotherms. Since the heights of the –10°C and –15°C isotherm were rarely observed directly on a PPI elevation angle display where the convective cell in question was located, interpolation between two different elevation angle scans often had to be performed. This interpolation was performed by looking at the PPI display of the elevation angle directly above and below the heights of the –10°C and –15°C isotherms, and using an average of the reflectivity values obtained from both.

For post analysis at NCSU, WSR-88D Algorithm Testing and Display System (WATADS) was used to display and analyze the collected Level II radar data. Individual convective cells were identified and tracked using the Storm Cell Identification and Tracking (SCIT) algorithm in WATADS (Johnson et al. 1998). A combination of PPI displays and vertical cross-sections were used to analyze the reflectivity values at the heights corresponding to the –10°C and –15°C isotherms within a convective cell. Convective cells within 100 km of KRAX (see Fig. 2) were randomly chosen and recorded on each of the case days.

To overlay the NLDN lightning onto the Level II radar data, several procedures had to be performed. First, a FORTRAN program took each ASCII file containing the NLDN lightning data for the entire U.S. and boxed off a region centered on Raleigh, North Carolina. Second, using a program called REORDER (Mohr 1986), the processed Level II radar data was interpolated to a Cartesian grid with 1-km horizontal resolution and 0.5-km vertical resolution. For each radar volume, five to six minutes of flash locations were overlaid onto a horizontal cross section of radar reflectivity at 0.5 km above ground level. In this fashion, the authors were able to correlate convective cells with individual CGs. Once it was determined that a convective cell produced lightning during a given radar volume scan, the exact time of the first lightning strike was recorded (accurate to the minute).

It is important to note that the radar data utilized in AWIPS was based on Level III data while WATADS used Level II WSR-88D data. As a result, the radar reflectivity images in WATADS were available at a higher resolution than in AWIPS (i.e., 256 data levels in WATADS versus 14 in AWIPS), at least at the time of this study. This loss of data resolution in AWIPS Level III based displays may have had some impact on the accuracy of visually identifying radar echoes that met a specific reflectivity threshold. Furthermore, there may have been some differences between the visual identification of cells using WATADS versus AWIPS. However, since the authors were only identifying echoes that exceeded 35 or 40 dBZ, this study did not require high resolution in radar reflectivity. It is therefore thought that any errors or differences in the methodology associated with AWIPS versus WATADS were small and minor.

Initially, lead times were calculated by starting from the volume scan where the criteria were first met. The time it takes the radar to scan up to the height of the –10°C or –15°C isotherm is on the order of a few minutes. Therefore, there was an inherent error in the lead time calculations. By looking at a height vs. range graph for different radar elevation angle scans and different volume scan strategies (either VCP-11 or VCP-21) it was found that there is an error of 2.50 minutes (VCP-11) to 4.50 minutes (VCP-21) in the starting time to reach the height of the –10°C or –15°C isotherm (Federal Meteorological Handbook No. 11 1991). Therefore, 3.50 minutes were subtracted from all of the lead times in this study that were calculated starting from the volume scan where the criteria were first met. If the initial lead time was less than 3.50 minutes, the adjusted lead time was 0 minutes.

Several standard meteorological statistical quantities were calculated in order to determine the accuracy of each set of WSR-88D based criteria for forecasting the CG lightning potential of a convective cell. These statistical quantities were the False Alarm Ratio (FAR), Probability of Detection (POD) and Critical Success Index (CSI; Wilks 1995). The FAR was calculated by taking the total number of false alarms and dividing that number by the total number of both false alarms and detections. The POD was calculated by taking the total number of detections and dividing that number by the total number of both detections and misses. The CSI was calculated by taking the total number of detections and dividing that number by the total number of detections, false alarms and misses.

3. Results and Discussion

Preliminary results show that the best set of lightning prediction criteria was either 1 Vol /40 dBZ/–10°C or 1 Vol /40 dBZ/–15°C (Fig. 3). Based on the CSI, the 1 Vol /40 dBZ/–10°C criteria performed best with a 100% POD, a 37% FAR, and a 63% CSI. The 1 Vol /40 dBZ/–15°C criteria closely followed with an 86% POD, a 30% FAR, and a

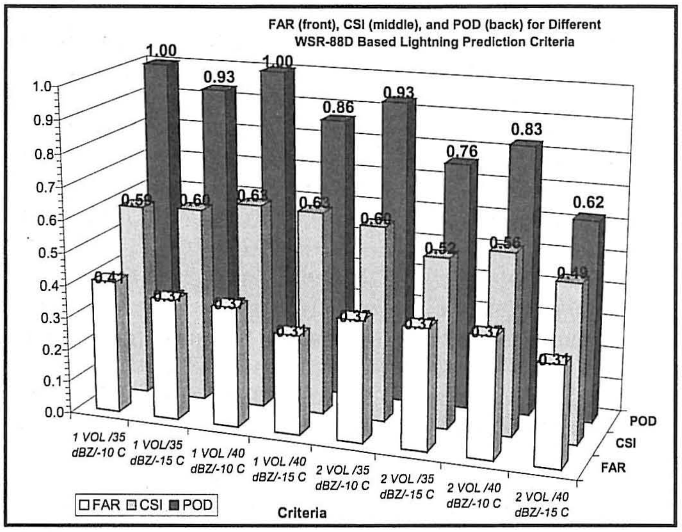

Fig. 3. FAR (no shading), POD (dark shading), and CSI (light shading) for different WSR-88D based lightning prediction criteria, which vary the number of volume scans (one vs. two), threshold radar reflectivity (35 dBZ vs. 40 dBZ) and isotherm height (-10°C vs. -15°C).

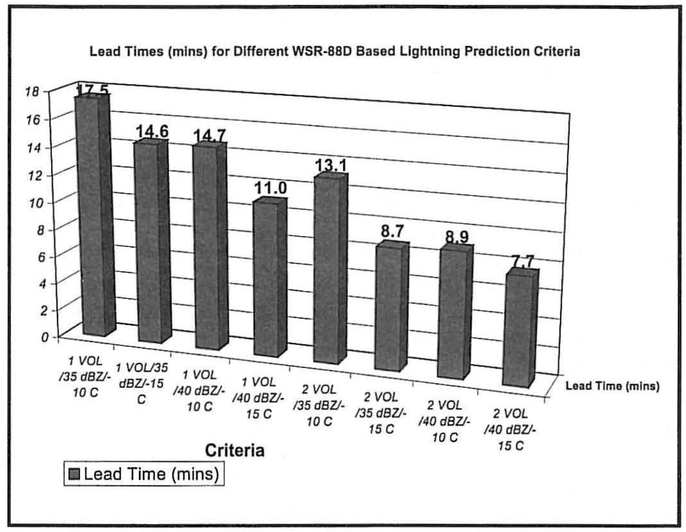

Fig. 4. Same as in Fig. 3, except for lead times (minutes).

62.5% CSI. Lead times for both of these criteria were 14.7 minutes and 11.0 minutes, respectively (Fig. 4).

The trends observed in the FAR, POD, CSI and lead times (Figs. 3 and 4) are consistent with expectations given the type of criteria used in the study. Shorter lead times were associated with criteria that utilized higher heights or colder temperatures (e.g., -15° C instead of -10° C). Convection took longer to penetrate to the colder temperature levels, resulting in reduced lead times. Criteria associated with colder temperatures also resulted in lower FARs because the convective cells that attained the more stringent criteria were deeper and likely characterized by stronger updrafts, more cloud liquid water, and increased graupel and hail production. As a result, there was a higher probability of significant charging and lightning occurrence in cells whose 35 dBZ to 40 dBZ echoes extended to colder temperatures or higher heights. On the other hand, the probability of lightning occurrence in a cell whose 35 dBZ to 40 dBZ isosurface reached only -10° C was non-zero. As a result, the POD was also lower for criteria utilizing colder temperatures (e.g., -15°C).

Increasing the reflectivity criteria from 35 to 40 dBZ had a similar effect as lowering the temperature criteria from –10°C to –15°C (Figs. 3 and 4). Convective cells took longer to attain the 40 dBZ reflectivity threshold, assuming it was reached at all. Therefore, raising the reflectivity from 35 dBZ to 40 dBZ in the lightning prediction algorithm decreased the lead times, FARs, and PODs in the same manner as lowering the temperature criteria.

As expected, increasing the number of volume scans in the lightning prediction criteria from one to two had the effect of decreasing the lead times (Fig. 4) because the other criteria had to be met for a longer period. The FAR was less (Fig. 3) because a convective cell that met the criteria for a longer amount of time was more likely to have a stronger updraft and was therefore more prone to produce lightning. The POD was smaller (Fig. 3) because a cell that did not meet the criteria for the larger number of volume scans sometimes still produced lightning.

The trends observed in the FAR, POD, CSI and lead times (Figs. 3 and 4) demonstrate that there is no advantage in requiring that conditions be met for two radar volume scans. Insisting that conditions be met for two radar volume scans decreased the POD, significantly reduced the lead time, and made little or no improvement in the FAR. The CSI was not very sensitive to the differentiation of the reflectivity threshold within the 35-40 dBZ range. For criteria using one volume scan, there was a slight increase in CSI when using 40 dBZ compared to 35 dBZ. Interestingly, this slight CSI advantage was reversed when two volume scans were used in the lightning prediction criteria (i.e., criteria using 35 dBZ were characterized by slightly larger CSIs than criteria using 40 dBZ for similar temperature thresholds and two volume scans). Lead times were noticeably better (2-3 minutes) for criteria using 35 dBZ. If lead time is a high priority and a slight increase in FAR can be tolerated, then 35 dBZ may be a better choice. Using colder temperatures (–15°C vs. –10°C) decreased the FARs but also resulted in a corresponding drop in PODs as previously discussed. Therefore, CSIs were almost identical when varying only temperatures. However, lead times were significantly better (3-4 minutes) when using –10°C as part of the criteria, so –10°C seems like a better choice.

For the nine additional late summer cases from 17, 27, 28 and 29 August 2001, the best lightning prediction criteria (based on the CSI) was again the 1 Vol /40 dBZ/–10°C criteria. These criteria resulted in an 87.5% CSI, a 100% POD, a 12.5% FAR and a 15.9 minute lead time. If a few more minutes in lead time is desired, and a higher FAR can be tolerated, the 1 Vol /35 dBZ/–10°C criteria may be a better choice with a 77.8% CSI, a 100% POD, a 22.2% FAR and a 19.4 minute lead time. The FARs for these additional cases were noticeably lower than for the primary cases investigated in the paper. Given the small number of late summer cases and the fact that they were only examined at the height of the –10°C isotherm, it is difficult to speculate on why the statistics for these cases are different than the statistics for the primary cases investigated. The lower FAR could be a result of increased instability and the pulse nature of convection in the late summer months or simply an artifact due to a limited sample.

4. Comparisons to Previous Studies

The results obtained in this study are comparable to those found in similar studies. Gremillion and Orville (1999) examined 39 airmass thunderstorms that developed over the NASA Kennedy Space Center in Florida. From a time series of radar echoes, they found that a 40 dBZ echo detected at the –10°C level was the best predictor of CGs with an average warning time of 7.5 minutes from when the criteria were met to when the first CG was observed. Using a reflectivity signature of 40 dBZ at the –10°C isotherm level yielded a POD of 84%, a FAR of 7%, and a CSI of 79%. They also noted that a 35 dBZ radar echo at the –10°C level was the second best predictor of CGs, with a POD of 88% and a FAR of 20%. A comparison of the results between this study and Gremillion and Orville's (1999) study is shown in Table 4.

Table 4. Comparison between this study and Gremillion and Orville (1999).

Researcher(s)	Criteria	FAR	POD	CSI	Lead Time
Gremillion and Orville	1 Volume Scan 40 dBZ at -10°C	7%	84%	79%	7.5 min.
This Study	1 Volume Scan 40 dBZ at -10°C	37%	100%	63%	14.7 min.

It is apparent that the study done by Gremillion and Orville had a significantly lower FAR than this study. Also noticeable is the shorter lead time (half as long) that they obtained. The difference in FARs and lead times may be explained by looking at the differences in the environments where the studies took place. The summertime Florida environment is characterized by rather significant instability due to strong diurnal heating and the nearby presence of large, rich moisture sources (Atlantic Ocean and Gulf of Mexico). The summertime Florida environment is also characterized by the almost daily occurrence of the sea breeze, which provides strong lift in the highly unstable environment. Therefore, summertime convection in Florida is often explosive, resulting in pulse-type intense thunderstorms. One would expect shorter lead times and lower FARs with convection of this nature, especially if the prediction criteria were rather stringent. Gremillion and Orville (1999) used a rather high reflectivity threshold of 40 dBZ at –10°C as their criteria for detecting CG lightning. A lower reflectivity threshold would act to increase lead times but would likely have increased the amount of false alarms as well (as seen in Figs. 3 and 4 for central North Carolina).

The speculation above is supported by the reduced FAR (13% to 22%) in this limited late summer sample from central North Carolina. The authors' hypothesis is that increased instability and hence updraft speed result in an enhanced probability of rapid vertical development of precipitation echo. According to the early studies of precipitation and cloud electrification, brisk vertical growth of radar echo is an important criterion for the subsequent production of lightning. As a result, increased instability would tend to lower FAR but could also reduce lead times because of the more rapid development of conditions necessary for cloud electrification. More case studies from a wide variety of thermodynamic conditions need to be analyzed in order to confirm this speculation.

Hondl and Eilts (1994) studied 23 thunderstorm cases in central Florida and obtained a median lead time of 14 minutes, 52 seconds and a mean lead time of 20 minutes, 2 seconds using a 10 dBZ echo at 0°C as the prediction criteria. They noted that 15 of 37 echoes exceeded the 10 dBZ threshold but did not evolve to produce any detected CG lightning. Based on the experience gained from this study, if the criteria used in the study by Hondl and Eilts (1994) were used in central North Carolina, very high FARs would be expected because a non-lightning producing 10 dBZ echo at 0°C is a fairly common occurrence in this region.

Buechler and Goodman (1990) studied 20 thunderstorm cases over Florida, Alabama, and New Mexico. Using a 40 dBZ echo at –10°C, they were able to predict the first CG lightning strike of a convective cell with a 100% POD, a 20% FAR, an 80% CSI, and lead times ranging from four to thirty-three minutes. By further constraining identification to storms whose echo tops exceeded 9-km (15 cases), they were able to obtain a 100% POD, a 7% FAR, and a 93% CSI. A comparison of the results between this study and Buechler and Goodman's (1990) study is shown in Table 5.

Table 5. Comparison between this study and Buechler and Goodman (1990).

Researcher(s)	Criteria	FAR	POD	CSI	Lead Time
Buechler and Goodman	1 Volume Scan 40 dBZ at -10°C	20%	100%	80%	4-33 min.
This Study	1 Volume Scan 40 dBZ at -10°C	37%	100%	63%	14.7 min.

The results obtained by Buechler and Goodman (1990) compare very well with the results obtained in this study. Since the cases in their study came from a couple of different regions, and since the lightning prediction criteria were the same, it is difficult to speculate on how they obtained a better FAR than in this study. However, as in the study done by Hondl and Eilts (1994), the low FAR is most likely a result of the environments in which the study took place or the result of a limited sample size.

Compared to other studies, the 37% FAR obtained in this study still seemed anomalously high. As a result, the vertical reflectivity structures of convective cells were investigated for possible differences. During the analysis of archived radar data in WATADS, differences were noted between the reflectivity structure of a convective cell that produced lightning and one that did not. The dif-

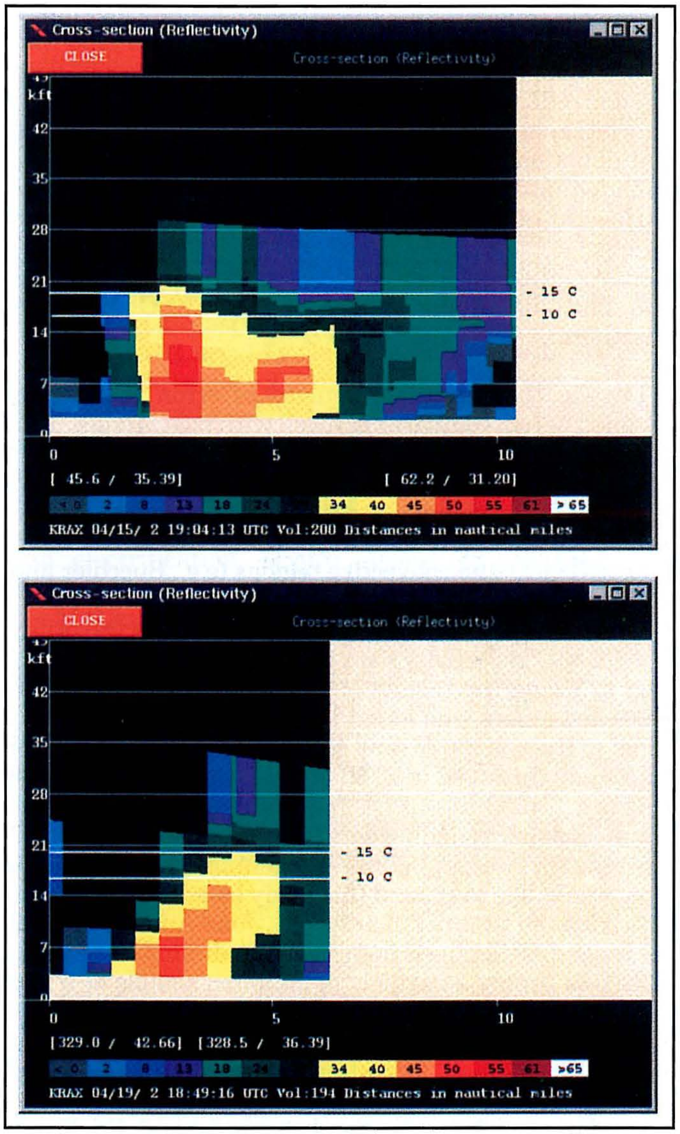

Fig. 5. Representative vertical cross-sections of radar reflectivity (dBZ, shaded) for examples of false alarms (heights in kft). Heights of the –10°C and –15°C isotherms are shown.

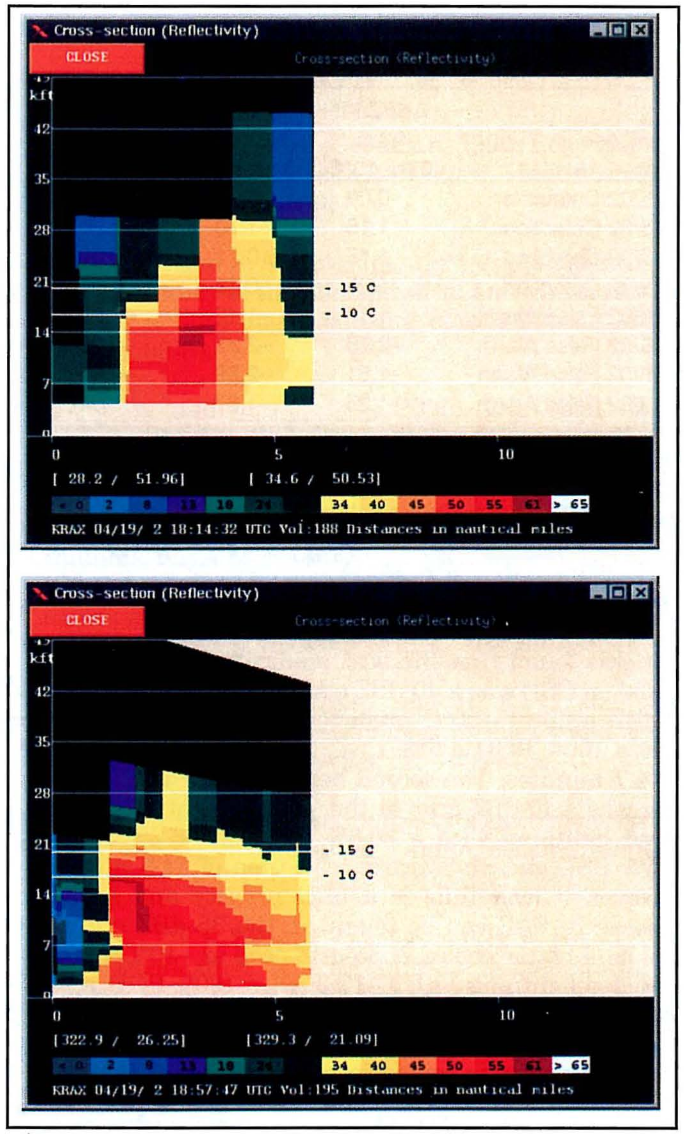

Fig. 6. Same as in Fig. 5, except for examples of detections.

ferences that were found in the analysis of archived data in WATADS were consistent with those found in past studies (e.g., Shackford 1960; Zipser and Lutz 1994). Zipser and Lutz (1994) found that convective cells over the tropical ocean that did not produce CG lightning contained large negative vertical gradients of reflectivity in the 0°C to –20°C temperature range, a direct result of weaker vertical velocities. They concluded that, as a necessary condition for rapid electrification, a convective cell must have its updraft speed exceed some threshold value (6-7 m s^{-1} mean speed and 10-12 m s^{-1} peak speed). In this study, the reflectivity structure of a convective cell that did not produce lightning was organized such that the center of highest reflectivity (on the order of 40-45 dBZ) was just below the height of –10°C and –15°C (Fig. 5). A convective cell organized in such a fashion usually just met the criteria for a lightning producing cell but did not produce lightning. The reflectivity structure of a convective cell that produced lightning generally contained a strong (45-50+ dBZ) echo that vertically extended well above the –10°C and –15°C heights (Fig. 6). The reflectivity gradients between the 0°C to –10°C, 0°C to –15°C, and 0°C to –20°C isotherm heights were analyzed for eight different cases (four detections and four false alarms). These eight different cases were chosen at random, with four cases coming from a dominant false alarm day and four cases coming from a dominant detection day. The results of the reflectivity gradient analysis are shown in Table 6.

Looking at Table 6, it is apparent that the false alarms cases had larger negative lapse rates in comparison with the detection cases. The mean reflectivity lapse rate between the 0°C and –20°C for a false alarm was –2.04 dBZ/kft and the mean reflectivity lapse rate between 0°C and –20°C for a detection was –0.69 dBZ/kft. Although there are a few outliers, the bulk of the data upholds the trends described above. Large negative lapse rates (–2.00 dBZ/kft or less) between the analyzed isotherm heights would suggest that the echo centroid of highest reflectiv-

Table 6. Reflectivity lapse rates between different isotherm heights.

Day/Case Type	ΔdBZ/kft from 0 to -10°C	ΔdBZ/kft from 0 to -15°C	ΔdBZ/kft from 0 to -20°C
4/15/02 Detection	0.00	0.00	–0.52
4/15/02 Detection	–1.15	–1.70	**–2.20**
4/15/02 Detection	1.15	0.71	0.52
4/19/02 Detection	–1.25	–0.75	–0.57
4/15/02 False Alarm	–1.15	–1.42	**–1.99**
4/15/02 False Alarm	**–2.76**	**–2.27**	**–2.30**
4/15/02 False Alarm	–1.61	**–2.69**	**–2.83**
4/19/02 False Alarm	–1.25	–1.37	–1.04

ity is located in warmer temperatures within the convective cell, thus indicating it is less probable that the cell in question will produce detectable CG lightning.

5. Summary and Conclusions

It was found that the best predictor of CG lightning (based on CSI) was a 40-dBZ echo at the –10°C height. A 40-dBZ echo at –10°C predicted lightning with a 37% FAR, a 100% POD, a 63% CSI, and an average lead time of 14.7 minutes. The second best predictor of CG lightning was a 40-dBZ echo at the –15°C height, which predicted lightning with a 30.6% FAR, an 86.2% POD, a 62.5% CSI, and an average lead time of 11.0 minutes. However, if lead time is a high priority and a slight increase in FAR can be tolerated, the 35 dBZ criterion may be a better choice. A 35-dBZ echo at –10°C criteria predicted lightning with a 41% FAR, a 100% POD, a 59% CSI, and an average lead time of 17.5 minutes.

False alarm cases had larger negative vertical reflectivity lapse rates in comparison with the cases that were detections. The mean reflectivity lapse rate between 0°C and –20°C for false alarm cases was –2.04 dBZ/kft and the mean reflectivity lapse rate between 0°C and –20°C for detection cases was –0.69 dBZ/kft. Large negative lapse rates between the analyzed isotherm heights would suggest that the echo centroid of highest reflectivity is located in warmer temperatures within the convective cell, thus indicating it is less probable that the cell in question will produce detectable CG lightning. Adding a vertical reflectivity gradient threshold between the 0°C and –20°C isotherm heights within a convective cell to the lightning prediction criteria would likely act to reduce the FAR and improve the CSI.

It was noted that there are several potential sources of error in this study. Discrepancies in the statistics (e.g., similar FARs for both the 1 Vol /40 dBZ/–15°C and 2 Vol /40 dBZ/–15°C criteria) are most likely the result of an inadequate sample size and a bias towards choosing cases that resulted in CG lightning in the former category. Other potential sources of error include:

- NLDN detection efficiency of less than 100%;
- variability associated with a natural range of microphysical and kinematic conditions leading to non-inductive charging and lightning;
- difficulty in identifying the presence of sufficient quantities of graupel, supercooled water and ice crystal concentrations sufficient for cloud electrification with radar reflectivity and temperature alone;
- variation in radar reflectivity due to power calibration, attenuation, range effects such as partial beam filling, inadequate sampling of vertical storm structure (Howard et al. 1997) and decreasing resolution with range;
- interpolation between different radar elevation angles to find the proper height of the –10°C or –15°C isotherm.

Despite these possible sources of error, the results obtained herein compare very well with past studies. This study demonstrates that it is possible to use WSR-88D reflectivity data to reasonably predict the onset of CG lightning in the central North Carolina region using criteria similar to that used in previous studies in other meteorological and convective regions (e.g., Buechler and Goodman 1990; Gremillion and Orville 1999).

For future work, the authors will investigate the utility of WSR-88D reflectivity data to nowcast "excessive" lightning following the results of Carey and Rutledge (1996, 2000) and others who found that CG lightning is proportional to the volume of echo centroid that exceeds a given reflectivity threshold (e.g., 30-40 dBZ) in the mixed phase zone (e.g., –10°C to –40°C). The authors will also explore thermodynamic sounding data for widely used indices that can reliably forecast lightning potential for a given day. They would like to expand this study by adding more case days from the summer months (i.e., June-August) to see if the lower FAR obtained from the limited sample of August cases was simply an artifact of a limited sample or a real signal due to a difference in the thermodynamic environment and convective structure during the summer months. In addition, the authors would like to try using zero-hour model soundings from the NOAA/NWS Rapid Update Cycle (RUC) or Local Analysis and Prediction System (LAPS) models so that the height of the –10°C and –15°C isotherms can be more accurately (spatially and temporally) ascertained. Finally, the ultimate goal is the automation of these WSR-88D procedures within AWIPS so that practical and timely short-term forecasting of CG lightning potential by NWS forecasters becomes feasible.

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