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

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1. INTRODUCTION

Forecasting the initiation of lightning activity is important for the protection of 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 6 to 7 km were closely associated with 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 among others) 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 Weather Surveillance Radar-1988 Doppler (WSR-88D) in the late 1980's and early 1990's, applied research and operational use of this knowledge showed that CG lightning strikes occurred soon (4-45 mins) after certain WSR-88D reflectivity values (10-40 dBZ) were reached at various isotherm (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).

The purpose of this study is to present operational meteorologists with a method of predicting the first lightning strike in a developing convective cell by utilizing WSR-88D reflectivity data to indirectly sample the electrification process and to discuss methods of refining the detection algorithm to improve its performance.

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2. DATA AND METHODS

The sample in this study consists of 50 cases (convective cells analyzed for CG lightning potential) taken from 13 lightning days (Table 1). Of those 50 cases, 24 cases were recorded in real time at the National Weather Service (NWS) in Raleigh, NC, 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, 9 additional cases from August 17, 27, 28 and 29, 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, NC) were obtained via the National Climatic Data Center (NCDC) for the following days in 2002: March 26, April 14, April 15, April 19, and May 30. The WATADS (WSR-88D Algorithm Testing and Display System) software was used to display and analyze the collected level II radar data. NLDN lightning data for the continental U.S. were obtained for the same days. Archived upper-air soundings from Greensboro and Morehead City, NC were also obtained. 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 Figure 1.

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	# 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)

Eight sets of criteria were used in analyzing the recorded convective cells. The criteria were comprised of the following 3 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 1 while varying the Z-threshold (35 or 40 dBZ) and environmental temperature (–10°C or –15°C) and criteria 5-8 hold the number of volume scans constant at 2 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 and MHX upper-air 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 Figure 2.

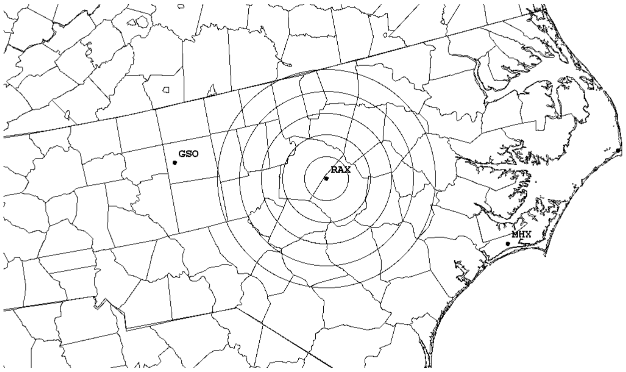

Figure 1. Map of study domain. The WSR-88D location (Raleigh, NC [RAX]) is shown with range rings at 20 kilometer increments out to 100 kilometers. The two upper-air stations used in the study (Greensboro, NC [GSO] and Morehead City, NC [MHX]) are also shown.

Table 2. Criteria sets that were used in analyzing convective cells for CG lightning potential.

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

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

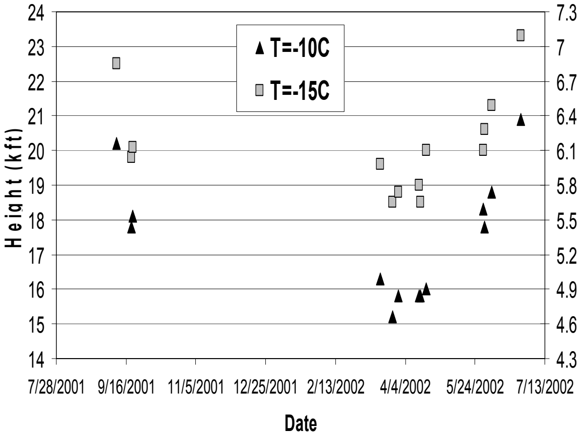

Figure 2. Time series of the heights of both environmental temperatures (-10°C and -15°C).

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.

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

Average Height of the –10°C Isotherm (kft)	Standard Deviation of the –10°C Isotherm (kft)	Average Height of the –15°C Isotherm (kft)	Standard Deviation of the –15°C Isotherm (kft)
17.4	1.8	20.2	1.5

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 (Figure 3). Based on the Critical Success Index (CSI), the 1 Vol /40 dBZ/–10°C criteria did the best with a 100% Probability of Detection (POD), a 37% False Alarm Ratio (FAR), and a 63% CSI. The 1 Vol /40 dBZ/–15°C criteria closely followed with an 86% POD, a 30% FAR, and a 62.5% CSI. Lead times for both of these criteria were 14.7 minutes and 11.0 minutes respectively (Figure 4).

The trends observed in the FAR, POD, CSI and lead times (Figures 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 FAR's 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 (Figures 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, FAR's, and POD's in the same manner as lowering the temperature criteria.

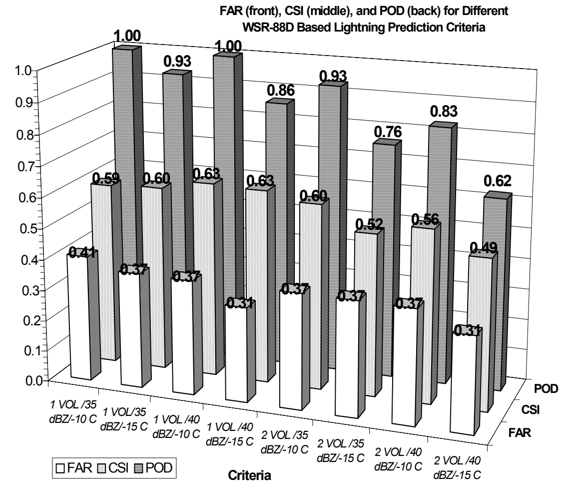

Figure 3. FAR, POD, and CSI for different WSR-88D based lightning prediction criteria, which vary the number of volume scans (1 or 2), the threshold radar reflectivity (35 or 40 dBZ) and the isotherm height (–10°C or –15°C).

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 (Figure 4) because the other criteria had to be met for a longer period. The FAR was less (Figure 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 (Figure 3)

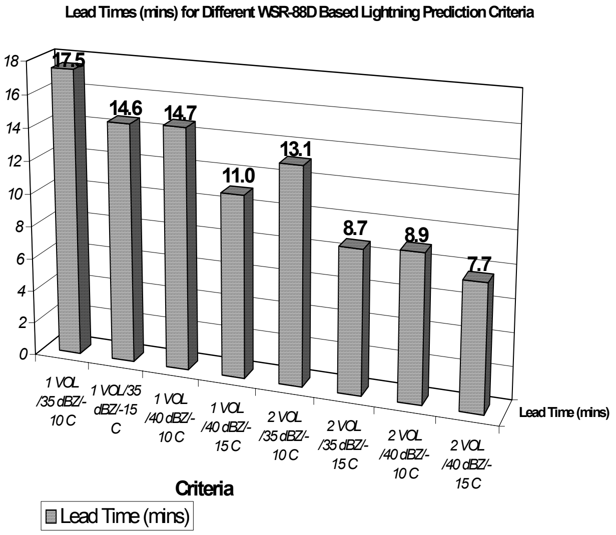

Figure 4. Same as Figure 3 except for lead times (minutes).

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 (Figures 3 and 4) demonstrate that there is no advantage in requiring that conditions be met for 2 radar volume scans. Insisting that conditions be met for 2 radar volume scans decreased the POD, substantially 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 CSI's than criteria using 40 dBZ for similar temperature thresholds and 2 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 FAR's but also resulted in a corresponding drop in POD's as previously discussed. Therefore, CSI's were almost identical when varying only temperatures. However, lead times were considerably 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 August 17, 27, 28 and 29, 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 are 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 FAR's 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. VERTICAL REFLECTIVITY ANALYSIS

Compared to other studies (e.g., Gremillion and Orville 1999; Hondl and Eilts 1994; Buechler and Goodman 1990), the 37% FAR obtained in this study 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 differences 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, which did not produce CG lightning, contained large negative vertical gradients of reflectivity in the 0°C to –20°C temperature range and that this was a direct result of weaker vertical velocities. Zipser and Lutz 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 (Figure 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 (Figure 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 8 different cases (4 detections and 4 false alarms) in hopes of finding an additional criterion to help lower the FAR. These 8 different cases were chosen at random, with 4 cases coming from a dominant false alarm day and 4 cases coming from a dominant detection day. Looking at the results in Table 4, it is apparent that the false alarm cases had larger negative lapse rates in comparison with the detection cases. The mean reflectivity lapse rate between 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 0°C and –20°C 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.

Table 4. Reflectivity lapse rates between different isotherm heights. Bold values represent relatively large negative vertical reflectivity lapse rates (<2.00 dBZ/kft).

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
4/19/02 Detection	–1.15	–1.70	**–2.20**
4/19/02 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

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 for one volume scan. 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 for one volume scan. A 40 dBZ echo at –15°C 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. The 35 dBZ 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

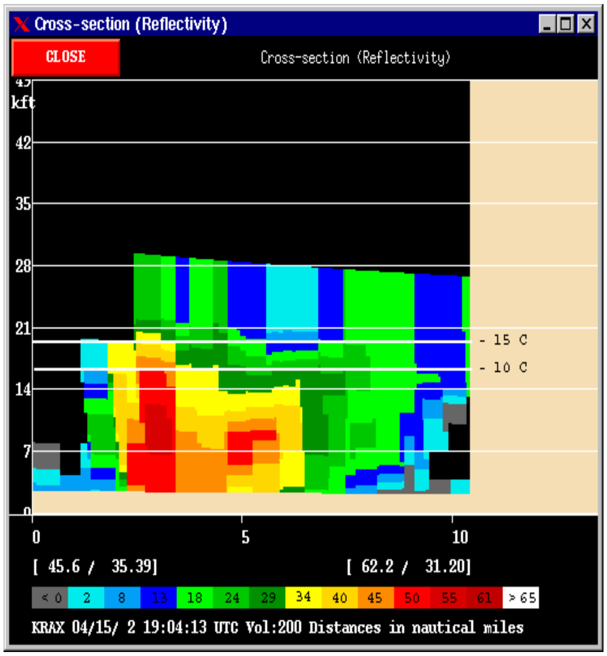

Figure 5. Representative vertical cross-section of radar reflectivity (dBZ) for example of false alarm (heights in thousands of feet). Heights of the –10°C and –15°C isotherms are shown.

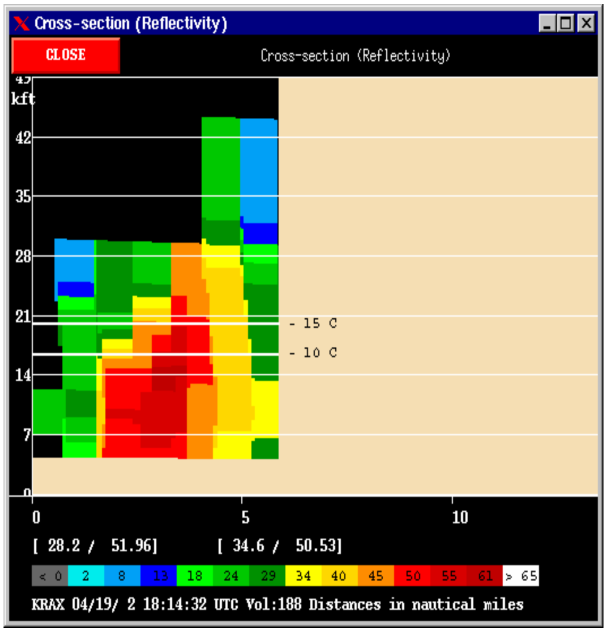

Figure 6. Same as Figure 5 except for example of detection (lightning produced).

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. Our study demonstrates that it is possible to use WSR-88D radar reflectivity 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, we would like to expand this study by adding more case days from the summer months (i.e., June, July, 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 RUC or 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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