5.691 Development and Testing of Operational Dual-polarimetric Radar Based Lightning Initiation Forecast Techniques

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1. INTRODUCTION

Lightning is one of Earth's natural dangers, destructive not only to life but also physical property. According to the National Weather Service, there are on average 58 lightning fatalities each year, with over 300 related injuries (NWS 2010). The ability to forecast lightning is critical to a host of activities ranging from space vehicle launch operations to recreational sporting events. For example a single lightning strike to a Space Shuttle could cause billions of dollars of damage and possible loss of life. While forecasting that provides longer lead times could provide sporting officials with more time to respond to possible threatening weather events, thus saving the lives of player and bystanders. Many researchers have developed and tested different methods and tools of first flash forecasting, however few have done so using dual-polarimetric radar variables and products on an operational basis. The purpose of this study is to improve algorithms for the short-term prediction of lightning initiation through development and testing of operational techniques that rely on parameters observed and diagnosed using C-band dual-polarimetric radar.

2. METHODOLOGY AND TOOLS

Using ARMOR (Advanced Radar for Meteorological and Operational Research), a C-band dual-polarimetric radar, data is collected on convective storms in the Huntsville-Northern Alabama area (Petersen et al. 2007). A PPI (plan position indicator) sector volume scan with excellent vertical coverage every 2-3 minutes is employed to optimize data quality. This data is then processed to correct for precipitation attenuation and differential attenuation (Bringi et al. 2001). A modified NCAR fuzzy-logic based particle identification (PID) algorithm for C-band polarimetric radar is used to process the data and estimate the particle types associated with the radar scans (Deierling et al. 2008, Vivekanandan et al. 1999). The soundings used to determine the temperature profile associated with each case is provided by the Redstone Arsenal or created using a linear average of the Birmingham and Nashville soundings. Using the sounding and the scan strategy, an optimum distance from the radar for quality vertical coverage of cells is determined. The NAL LMA (Northern Alabama Lightning Mapping Array), a network of 10 time-of-arrival VHF total lightning sensors, is used to determine first lightning flash for cells in optimum range from the radar (Goodman et al. 2005).

These cells are then evaluated for spatial distinction from other convective systems and radar coverage. This means that each cell is observable within the radar sector volume scans from initial formation to first flash and must be distinguishable and relatively independent from convective systems, such as a squall line, where cells typically closely interact. An area of interest is visually assessed for each cell that meets the previously stated criteria. The interest area is defined by a Z_h reflectivity threshold at a temperature level of importance (30 dBZ at -10˚C). The temperature level is based on the NIC (non-inductive charging) method in which charge separation occurs by chance collision of large ice particles with smaller crystalline particles in the presence of supercooled liquid (Reynolds et al. 1957). The -10˚C level is approximately the lower location of the main negative charge layer created by charge separation based on the tripole model (e.g., MacGorman and Rust 1998). Reflectivity values greater than 30 dBZ imply the larger precipitation sizes, such as graupel and small hail, and concentrations required for significant electrification. For example, the 45th Weather Squadron has used reflectivity ≥ 35 dBZ

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reaching -10°C with depth and duration thresholds to forecast the first lightning flash for many years in support of America's space program at Cape Canaveral Air Force Station and Kennedy Space Center in Florida (Roeder and Pinder 1998). Visual tools such as SOLOII, an NCAR radar sweep file viewer, and ANGEL (Analysis of NEXRAD, GPS, EDOT, and LMA), UF (universal format) radar and LMA lightning viewer, are used to evaluate cells.

Once a cell of interest is identified and defined, polarimetric radar parameters within the area of interest from levels above and below the target height are extracted from quality controlled UF radar data to a text file. These values that are required approximately meet the criteria of the test algorithms listed in Table 1.

The Z_h and temperature thresholds serve as controls for this study. Reflectivity thresholds at a given temperature level have been previously studied and employed as a forecasting technique for non-polarized Doppler radars (Buechler and Goodman 1990, Dye et al. 1989, Gremillion and Orville 1999, Roeder and Pinder 1998, Vincent et al 2003, Yang and King 2010). For example reflectivity values above 35 dBZ located in levels at temperatures below freezing are consistent with the presence of mixed phase precipitation processes required for electrification (i.e., graupel and super-cooled water). "First instance" in this study is defined as the first occurrence of a single value (PID or dBZ) at a defined temperature threshold, as seen in Fig. 1. This can be a value linearly interpolated between two elevation scans for greater accuracy (as employed for Z_h). Others have used Layered VIL above 0C to forecast the onset of lightning, which requires both enough vertical motion and depth of the updraft for charge generation and charge separation for the onset of lightning (Roeder and McNamara 2011)

PID is a modified NCAR fuzzy-logic based particle identification (PID) algorithm for C-band polarimetric radar (Deierling et al. 2008, Vivekanandan et al. 1999). PID was chosen as a test variable for its ability to represent the wide suite of variables that a dual-polarimetric radar is capable of producing. These variables have been studied extensively and a trend of values for each can be associated with particular hydrometeor types due to their innate characteristics (Lim et al. 2005, Vivekanandan et al. 1999). PID categories are based on bulk hydrometeor identification, meaning that each radar value is representative of a volume of the storm which contains various hydrometeor sizes and types. For this reason categories are grouped together into lightning-relevant categories, e.g. graupel. Graupel and large ice particles are one of the key factors in cloud electrification. The "dominant value" is determined by the majority quantity of grouped radar range gate values in the interest area (e.g., Fig. 2).

Z_{dr}, differential reflectivity, is a measure of reflectivity-weighted particle oblateness and is calculated as follows: $Z_{dr} = 10*LOG10(z_h/z_v)$. Rain drops deform to become more oblate as they grow in size (e.g., exhibit a larger z_h than z_v), thus typically returning positive Z_{dr} values ranging from 0.5 to 5 dB at C-band. Nearly spherical, tumbling hail/graupel have an averaged Z_{dr} value near zero (-0.5 - 0.5dB) and moderate to large reflectivity (Z_h > 35 dBZ). With these observations in mind, Z_{dr} combined with larger Z_h (size and concentration) can be used to determine approximate hydrometeor type (Bringi et al. 1984). High Z_{dr} values (Z_{dr} > 0.5dB) occurring with large values of Z_h, as can be examined in Fig. 3, are referred to as a Z_{dr} column. A Z_{dr} column in warm cloud base storms that extends through the altitude of the freezing level is an indication that super-cooled raindrops exist that may later freeze into hail if the convective cell persists in time. These Z_{dr} column signatures could provide early warning of large precipitation ice and lightning.

3. DATA AND CONCLUSIONS

The data collected are obtained from 8 thunderstorm cells from two case dates, 8 July 2008 and 18 June 2010. For both case dates, the storms were products of isolated diurnal summer convection that is typical to the Northern Alabama region. These cells were chosen since they are thought to be reasonably close to the type of convection typically experienced by the space launch customers of 45th Weather Squadron in Florida. See Table 2 for lead times and probability of detection associated with these storms.

Table 2 suggests, as expected, that the more stringent the requirement is made for a threshold to be met, the smaller the lead time and the lower probability of detection (POD). This is particularly evident in decreasing lead times and POD associated with applying decreasing temperature (increasing height) thresholds. The reflectivity threshold of 35 dBZ at -10˚C has the best lead time with high POD. This lead time and the other lead times of Z_h and temperature are comparable to previous studies and are consistent with the operational procedures used at 45th Weather Squadron.

When examining PID categories and time evolution of the cells in these cases, ice and snow are dominant initially, followed by the formation of graupel, which is also observable in the Z_{dr} value trends in Fig. 4. PID categories containing hail in smaller quantities are present just prior to first flash. The first instance of any large ice at -10˚C is close to the same detection leads as using the first occurrence of $Z_{dr} > 0.5$ dB with the same POD. Thus the advantages of using PID of large ice hydrometeors over the Z_{dr}-based identification of super-cooled raindrops are not significant; however this might prove otherwise with further testing. First instance for large ice produces a greater POD and lead time opposed to PID dominate value. While a greater amount of ice is ideal for electrification to occur, it is not necessary. When used as a forecasting tool, PID dominate value adds a greater requirement that, once again, reduces POD and lead time. At this stage in the study, the value of using dual-polarimetric PID for improving lead time or POD is questionable for this limited sample. Further research may provide a stronger case with a larger sample and non-electrified storms to test false-alarm-rates and other skill scores.

Errors in results may derive from the subjective methodology of selecting area of interest. The potential bias of the sample due to the small size and lack of non-thunderstorm cases limits our ability to generalize the results. The limited sample size may also contribute to errors in POD and lead times.

4. FUTURE WORK

Ongoing/future work includes expanding the data set to include more thunderstorm cases and a set of non-thunderstorm cases. With non-thunderstorm cases, expansion of skill scores will include False Alarm Ratio (FAR), Critical Success Index (CSI), Heidke Skill Score (HSS) and or True Skill Statistic (TSS), and Operational Utility Index (OUI) (D'Arcangelo 2000). The OUI is an index developed by the 45th Weather Squadron that gives more weight to POD since personnel safety is involved, some weight to skill, and less weight to low FAR. The UI might be expanded to include lead-time, perhaps fraction of desired lead-time (30 min). The value of dual-polarimetric radar-based algorithms may be in reducing false alarms as will be investigated with the inclusion of non-thunderstorm cases into the data set. Further more, testing of additional dual-polarimetric radar-based algorithms will be conducted on current and future cases. Such additional tests will include PID first instance of small ice particles and supercooled drops. Small ice particles under go riming to eventually form larger ice particles such as graupel. Riming at temperatures below -10˚C requires super-cooled drops, thus detection of ice crystals or super-cooled drops might increase lead times associated with first flash forecasting. A secondary upper level Z_h and temperature threshold will be added to singular lower level Z_h and temperature thresholds to determine if updraft strength associated with the lofting of particles to higher altitudes and convective formation will reduce FAR. This provides support that the depth of the storm is conducive to support charge separation as required by the NIC charge method. Especially important will be quantifying the performance gain of Z_{dr} towers, especially improved lead-time, in predicting the first lightning flash compared to traditional reflectivity techniques.

5. FIGURES AND TABLES

Table 1. A table of algorithms tested on the data set. Each algorithm of each test set (1-3) consists of a single criteria or value from each column, such as the first occurrence of Z_h value 35 dBZ at the height of the -10˚C thermal level. The Z_h values associated with the Z_{dr} test algorithms include 35 dBZ and 40 dBZ.

Test	Focus	Threshold Values	Temperature Level	Criteria
1	Z_h and temp	35, 40, 45 dBZ	-10, -15, -20 C	First occurrence of Highest value
2	PID and temp	6<PID>9 (any large ice) PID = 8,9 (graupel)	-10, -15, -20 C	First instance, and dominant value
3	Z_{dr} and Z_h with temp	>1dB , >0.5dB	-10, -15, -20 C	First instance of highest value

Table 2. Results from algorithms tested of Lead times/Probability of Detection (POD). Lead times are displayed in minutes. 35 dBZ at -10˚C has the best lead time associated with a high (100%) probability of detection for this data set.

Temperature		-10° C	-15° C	-20° C
Z_h (dBZ) first instance	35	14.14 / 1	11.51 / 1	7.41 / 0.875
	40	11.74 / 1	8.68 / 0.875	2.40 / 0.75
	45	9.87 / 0.875	2.52 / 0.625	0.43 / 0.375
PID first instance	Large ice	12.38 / 1	8.48 / 0.875	2.99 / 0.75
	graupel	12.38 / 1	8.48 / 0.875	2.99 / 0.75
PID dominant value	Large ice	9.86 / 1	0 / 0	0 / 0
	Graupel	6.68 / 0.875	0 / 0	0 / 0
Z_{dr} (dB) column &Z_h (dBZ)	>0.5 & 35	13.02 / 1	11.13 / 1	6.79 / 0.875
	>0.5 & 40	11.48 / 1	7 / 0.875	2.09 / 0.625
	>1 & 35	13.02 / 1	8.39 / 0.875	1.80 / 0.625
	>1 & 40	11.48 / 1	3.51 / 0.75	0.69 / 0.375

Table 3. Table of the categories and colors representations of the NCAR bulk-hydrometeor particle identification algorithm.

Category	Color	*NCAR PID*
1		*Cloud*
2		*Drizzle*
3		*Light Rain*
4		*Moderate Rain*
5		*Heavy Rain*
6		*Hail*
7		*Rain and Hail*
8		*Graupel and Small Hail*
9		*Graupel and Rain*
10		*Dry Snow*
11		*Wet Snow*
12		*Ice Crystals*
13		*Irregular Ice Crystals*
14		*Supper-cooled liquid drops*
15		*Flying Insects*
16		*Second Trip*
17		*Ground Clutter*

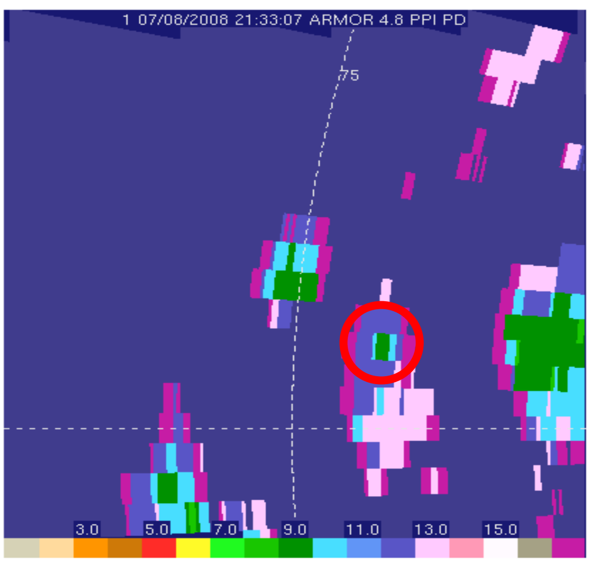

Figure 1. ARMOR PPI image of the modified NCAR PID output at 4.8° elevation angle for case date 20080708. The red circle indicates the area of interest of Cell 1. This is the first occurrence of graupel PID category (see Table 3) for this cell.

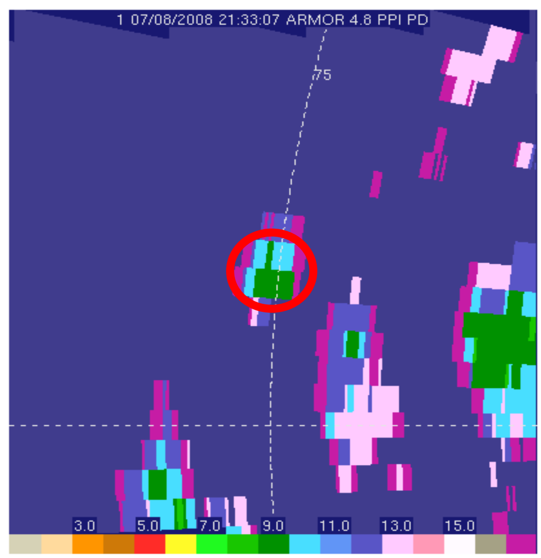

Figure 2. ARMOR PPI image of the modified NCAR PID output at 4.8° elevation angle for case date 20080708. The red circle indicates the area of interest of Cell 2. The Graupel PID category is the dominate particle category in the interest area of Cell 2.

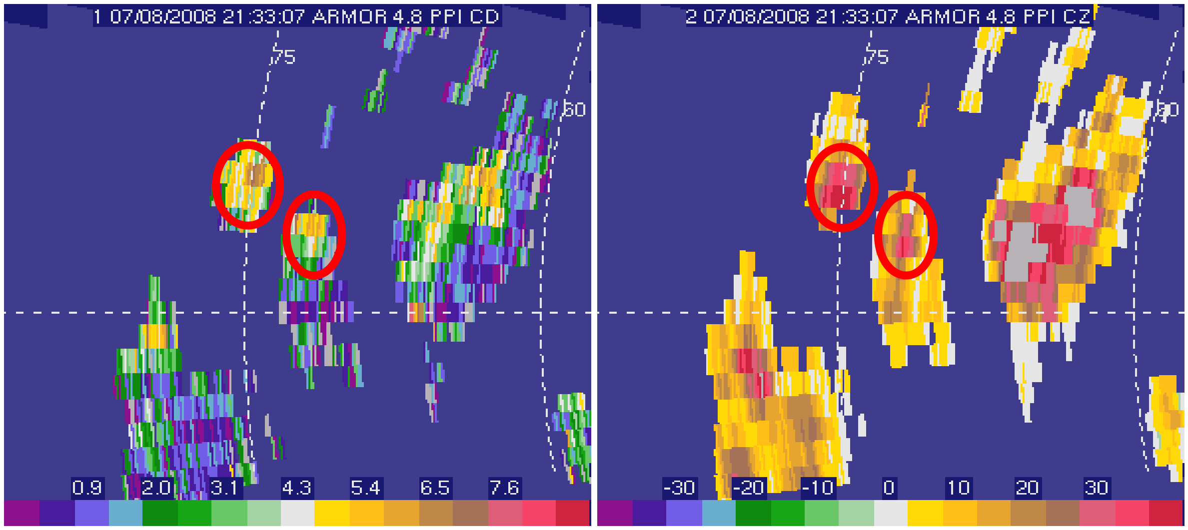

Figure 3. ARMOR PPI image of corrected horizontal reflectivity (right) and differential reflectivity (Z_{dr}) (left) at 4.8° elevation angle for case date 20080708. The red circles indicate the areas of interest of Cell 1 (right) and Cell 2 (left).

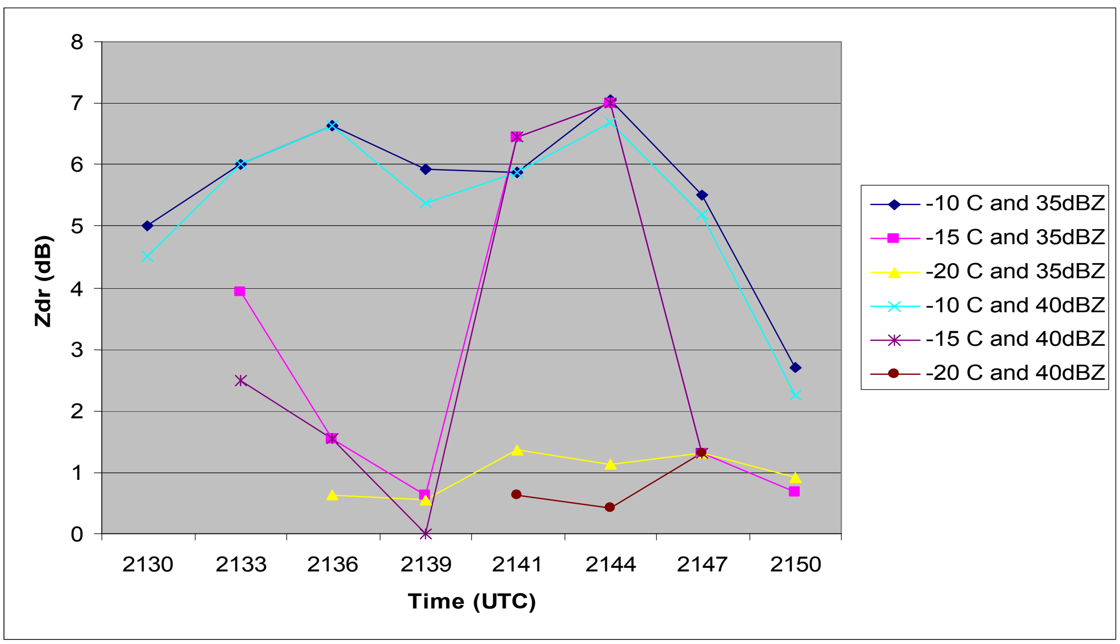

Figure 4. Temporal evolution of maximum Z_{dr} values for different temperature levels (-10˚C to -20˚C) and Z_h thresholds for Cell 1 of 20080708. The first flash occurred at 2148 UTC.

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