American Meteorological Society, 26th Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, Atlanta, GA, 17-21 January 2010

11B.1 LIGHTNING THREAT NOWCASTING WITH POLARIMETRIC RADAR

James J. Stagliano

Propagation Research Associates, Inc.

1 INTRODUCTION

Cloud to ground (CG) lightning causes nearly a billion dollars of property damage and approximately 90 fatalities a year. Yet lightning warning facilities are minimal at best, with most warnings occurring after the first strike and have no forecast capability before the first few strikes. First strike events continue to lead is causing significant fatality and injury, even with the lightning warning systems providing notification such as the event in Bonaire, Georgia September 11, 2008 where an initial strike during a football game at the Bonaire Middle School sent 13 people to the hospital.

A significant source of lightning concern are sporting activities that are played in open areas such as baseball, softball, football, soccer, and golf. In 1997, NOAA conducted a study of 3,239 lightning deaths over 35 years (Curran, 1997). They found that five times more people are killed by lightning in open fields or parks. Playgrounds and parks accounted for nearly 27% of lightning deaths, and golfers accounted for 5% of deaths during the period. Table 1 below shows the results of the NOAA study.

Table 1. Lightning fatality statistics 1959-1994 (Curran, 1997)

Activity	Deaths	Percent
Open field, park, playground, etc.	868	26.8%
Under trees	444	13.7%
Water related, fishing, boating, swimming, etc.	262	8.1%
Golf course, including sheltering under trees	159	4.9%
Driving tractors, farm equipment, heavy road equipment, etc.	97	3%
Telephone related	78	2.4%
Radios, transmitters, aerials	23	0.7%
Other/Unknown	1,308	40.4%

On the other hand if you assume that 50% of the U.S. population visits open fields, parks, or playgrounds at least once each year and that half of them can be found at least occasionally under trees, the statistics indicate the likelihood is one lightning death per 5.3 million visiting open fields, parks, or playgrounds, and one in 5.2 million of those wandering under trees. Furthermore, these statistics do not account for injuries that occur due to lightning every year which will be far greater in number than deaths. Clearly an early warning system would reduce death and injury due to lightning.

A technique for nowcasting the threat of cloud to ground lightning with polarimetric weather radar is described. The technique is based upon a simple electrification model of convective storm cells and the ability to classify hydrometeors within the cell. The technique subsequently uses the probability density functions implemented by Stagliano (2009) to describe the threat of cloud to ground lightning.

2 ELECTRIFICATION MODEL

The electrification model refers to process by which charge is separated within the cloud, creating the significant electric field and subsequent electrical discharge we call lightning. Though this simple model explained herein cannot explain the complex charge structure within a cloud, it captures the essence of algorithm to nowcast and forecast CG lightning.

The model begins with moist air rising into the atmosphere. As it rises, it expands and cools, condensing into water droplets. As the water droplets rise above the -10^{o}C level, ice crystals begin to form. The ice crystals grow into graupel through the riming process. As graupel is formed, the radar signature begins to be become significant. The graupel descends, colliding with ice crystals at lower altitudes. The collisions result in charge transfer between the graupel and the ice crystals. The ice crystals and graupel are subsequently advected to higher altitudes through updrafts, with the ice crystals reaching a higher altitude. The result is charge separation and an associated electric field. As the electric field increases, the temperature at which ice can form increases, providing a positive feedback mechanism for the charge separation and electric field generation.

The important aspects of this process are the development of the ice crystals and the graupel. The graupel is carried by the updrafts into the upper reaches of the convective cell. Therefore, there is a physical separation between the maximum height attained by the graupel and the height at which the ice crystals form. It is this separation that forms the basis for the probability density functions used to nowcast the cloud to ground lightning threat.

3 LIGHTNING PREDICTION SYSTEMS

Current lightning prediction systems fall into two categories, those requiring strikes to provide warning and those that can predict before the first strike. They also come in a variety of sizes from national networks to hand held detectors and utilize different techniques and technology.

3.1 Post Strike Prediction Systems

Post strike prediction systems rely on a single or multiple strikes to provide warning of lightning threat. These units fall into two categories, small hand held units that register strikes

Corresponding Author: James J. Stagliano, Propagation Research Associates, 1275 Kennestone Circle, Suite 100, Marietta, GA 30066
jim.stagliano@pra-corp.com

within a certain range, and systems that utilize data from a lightning detection network.

The former come in a variety of sizes from small handheld units to antennas that connect to a PCI card within a computer. Both of these units detect the electromagnetic pulse produced by the discharge. The hand held units estimate the distance from the sensor to the discharge and gives visual and audible warnings of lightning strikes in the area.

The computer based sensor operates similarly. However, it utilizes a directional antenna and associated signal processing to determine the location, range and azimuth of the discharge. The result is displayed on a georeferenced display on the computer screen.

The second type of post strike prediction system utilizes a network of lightning detection sensors to determine the location and characteristics of the discharge. A number of discharge events are needed to estimate the advection of the lightning. From the time series, nowcasts of lightning threat are produced.

Obviously lightning warning using the post discharge devices are insufficient to warn before the first strike or lightning initiation. In the Bonaire event, the responsible parties had a hand held device but it did not give sufficient warning to allow players and spectators to clear the field before the strike.

3.2 Pre-Strike Prediction

Prestrike lightning prediction utilizes data which are precursors to lightning generation. The precursors include the electric field at the ground and characteristics of certain radar products.

The electric field is a measure of the electrical potential energy due to the difference in charge between two surfaces (cloud and ground). When the electric field attains a critical value, the breakdown potential, discharge can occur. The electric field is measured with an electric field mill sensor which in its basic form alternately exposes and shields electrodes from the background electric field. This results in a current produced between the electrodes that is proportional to the electric field strength.

The primary issue with these kinds of meters is threat the breakdown voltage varies with atmospheric conditions and thus with different climatic regimes and/or times of the year. Thus warning threshold that applies in Florida is not applicable to elsewhere. This of course is not a problem provided tuning is performed for a particular installation. The tuning requirements will require significant amounts of event data.

As with the handheld and the smaller computer based post strike sensors, electric field monitors can be relatively portable and be collocated with audible warning systems.

A second pre-strike prediction technique uses radar products as a proxy for the lightning threat potential. A number of manufacturers use different products such as vertically integrated liquid and echo tops products to derive some estimate of the likelihood of lightning. These techniques of course rely on the availability of radar data. The advantage of this technique is the ability to begin forecasting as the cells develop. In the next section a simple radar product technique is explored.

4 LIGHTNING NOWCASTING VIA RADAR

A number of studies have indicated a correlation between cloud to ground (CG) lightning and relatively high radar reflectivity values attained at significant altitude. Vincent (2003) and later Wolf (2007) described a relatively simple correlation between CG lightning strikes 10-20 minutes after volume collection and the altitude associated with the 40 dBZ reflectivity level with respect to the height of the -10℃ level of the collected data volume. Wolf (2007) extended the correlation to include "frequent" (greater than 10 strikes in a 5-minute period) and "numerous" (greater than 20 strikes in a 5-minute period) CG activity. Figure 1 shows the probability for the different states, no CG lightning, CG lightning, frequent CG lightning, and numerous CG lightning (Wolf, 2007) with respect to the relative height of the 40-dBZ radar reflectivity to the -10℃ altitude. For the algorithm, the probability density functions described in Figure 1 are transformed into piece-wise third-degree polynomials through the fitting of the data with cubic splines. There is one set of functions for each characteristic data set (CG, Frequent CG, and Numerous CG).

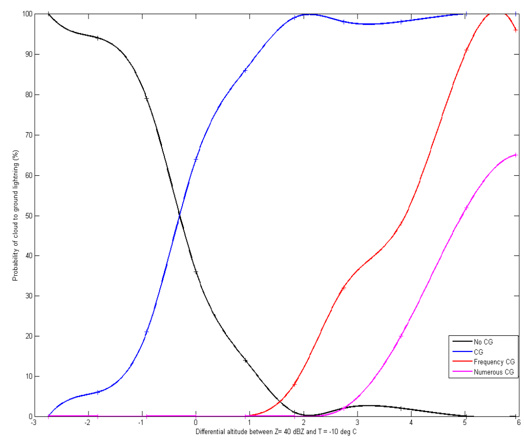

Figure 1. CG lightning probability as a function of the height of the 40 dBZ echo relative to the -10℃ level .

4.1 Lightning Nowcast Algorithm for Singularly Polarized Radar

Stagliano (2009) implemented a cloud to ground nowcast algorithm for weather radar based using the probability density functions of Figure 1 and the algorithm for nowcasting the threat of cloud to ground lightning is shown in Figure 2. Essentially the difference in height between the maximum height of some reflectivity threshold (a proxy for graupel) and the height of the -10 degree Celsius level (a proxy for ice crystal formation) is inserted into the probability density functions.

The inputs to the lightning threat algorithm are the radar reflectivity threshold (nominally 40 dBZ) (Z_{th}), the height of the -10℃ level (h_{-10}), and the radar data volume. The algorithm begins by reading the radar data volume (Level II data) into memory. Each sweep or elevation slice is examined for radar reflectivity values greater than the threshold. Assuming a standard refractive atmosphere (4/3 R_E approximation), the height of a particular sample is given by (Rinehart, 1991),

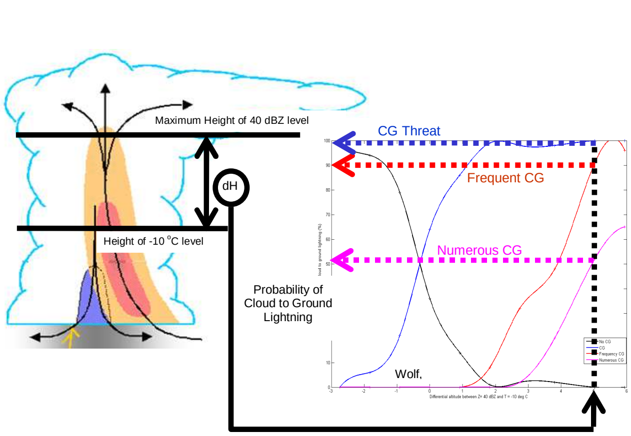

Figure 2 Graphical description of the lightning threat algorithm.

$$H = \sqrt{r^2 + R'^2 + 2rR'\sin(\phi_{el})} - R' + H_0\,, \qquad (1)$$

where r is the range from the radar, R' is the Earth's effective radius, $4/3R_E$, φ_{el} is the elevation angle, and H_0 is the antenna height above the ground. This height is projected onto the Earth's surface via a simple cosine relation,

$$R_{flat} = r\cos\phi_{el}\,. \qquad (2)$$

Once the entire volume has been traversed, the resultant geo-referenced product denoted by **H** gives the heights of radar reflectivity echoes greater than the threshold. Subtracting the height of the -10℃ level (h_{-10}) from **H** gives a new product of relative heights, relative to the -10℃ level,

$$\mathbf{H}_{litn} = \mathbf{H} - h_{-10}\,. \qquad (3)$$

The lightning probability is subsequently determined by applying the piece-wise polynomials to the product $\mathbf{H}_{litn}$. The result is three polar products representing CG, Frequent CG, and Numerous CG, respectively. These can be applied as raster layers to a mapping system or converted into vector quantities (shape files) for direct application in a mapping application.

Using a storm track algorithm, future locations of the convective cells may be extrapolated to provide a threat nowcast up to an hour into the future.

4.2 Lightning Nowcast Algorithm for Polarimetric Weather Radar

The lightning nowcast algorithm using polarimetric weather radar follows the same theme. In the singularly polarized radar the maximum height of the 40 dBZ level is used as a proxy for the maximum height attained by the graupel and the -10 degree Celsius level is used as a proxy for the formation of ice crystals. Polarimetric radar is unique in that by using the extra information provided by the polarimetric returns, the hydrometeors within a cell may be determined. Rather than using proxies, graupel and ice crystals can be identified and their associated heights used as input into the PDF's.

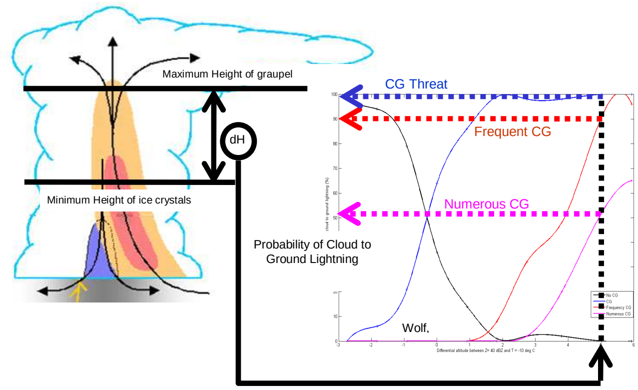

Figure 3 Graphical description of the polarimetric lightning threat algorithm.

The polarimetric algorithm is shown graphically in Figure 3. The difference between the maximum height attained by the graupel in the cell and the minimum height of the ice crystals within the scan area is inserted into the probability density functions, resulting in a quantitative estimate for the threat of cloud to ground lightning.

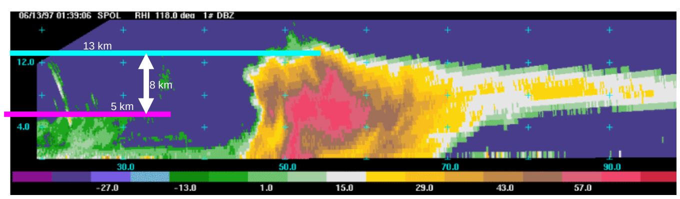

Figure 4 Reflectivity RHI of a cell located near Wichita, Kansas on June 13, 1997 . (Vivekanandan, 1999)

Vivekanandan (1999) performed hydrometeor classification on a cell near Wichita, Kansas on June 13, 1997. Figure 4 shows a reflectivity RHI. The cyan line (13 km) identifies the maximum height of the 40 dBZ level (the proxy for graupel), and the magenta line (5 km) shows the height of the -10 degree Celsius level (the height at which ice crystals form). Finding the difference in these two heights (8 km) and inserting the result into the PDF's, the probability of cloud to ground lightning from this cell is 100% for any cloud to ground lightning, 100% for frequent cloud to ground lightning (more than 2 strikes per minute) and 60% for numerous cloud to ground lightning (more than 4 strikes per minute).

Figure 5 shows the hydrometeor classification associated with the cell shown in Figure 4. The cyan line (13 km) shows the maximum height attained by the graupel. This is surprisingly exactly at the same height as the proxy for graupel used in the reflectivity data. The magenta line is the line associated with the lowest height of the ice crystals (5 km), this should be the height the ice crystals formed. Again, this is very close to the proxy of -10 degrees Celsius. Thus, again the resulting threat of cloud to ground lightning strikes are the probability of cloud to ground lightning from this cell is 100% for any cloud to ground lightning, 100% for frequent cloud to ground lightning (more than 2 strikes per minute) and 60% for numerous cloud to ground lightning (more than 4 strikes per minute).

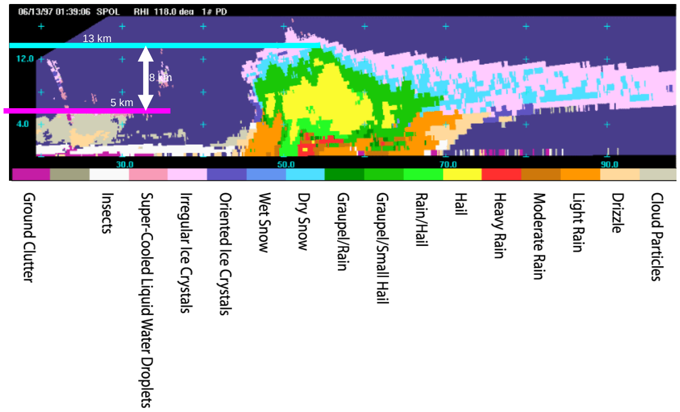

Figure 5 Hydrometeor classification RHI for cell in Figure 4. (Vivekanandan, 1999)

It is important to note that within the cell itself, the ice crystals were not at the minimum height, the height of formation, rather they were in the anvil. The minimum height for the ice crystals was determined in a cloud closer to the radar. Operationally, if the minimum height of the ice crystals within the volume is much different than the -10 degree Celsius level, the latter would be used in the algorithm.

5 CONCLUSION

An algorithm for nowcasting the threat of a cloud to ground lightning strike using polarimetric weather radar is presented. The algorithm first performs the hydrometeor classification. The volume is searched for the lowest height of the ice crystals and the highest altitude of the graupel. The difference between these altitudes is inserted into empirically determined probability density functions which output the probability of any cloud to ground lightning, frequent cloud to ground lightning (more than 2 strikes per minute) and numerous cloud to ground lightning (more than 4 strikes per minute). Extrapolating the kinematic information from the storm track utility provides high temporal resolution forecasts for the following 20 to sixty minutes.

We assessed a demonstration case (Vivakanadan, 1999) that included both the reflectivity and hydrometeor classification RHI. In this particular case, the proxies matched the associated classifications very well resulting in essentially identical lightning threat nowcasts for the studied cell.

Future work involves implementing the polarimetric algorithm and assessing its performance with lightning strike data.

6 ACKNOWLEDGEMENTS

This work was funded by the National Weather Service under contract WC133R-08-CN-0142**.**

7 REFERENCES

Bringi, V.N. and V. Chandrasekar, 2001: **Polarimetric Doppler Weather Radar**, Cambridge University Press, pp. 636.

Brown, B., R. Bullock, J.H. Gotway, C. Davis, D. Ahijevych, E. Gilleland, L. Holland, 2007: New tools for evaluation of numerical weather prediction models using operationally relevant approaches, *Battlespace Atmospheric and Cloud Impacts on Military Operations, 6-8 November, Chestnut Hill, Massachusetts*.

Conway, J.W. and M. Eilts, 2005: The Lightning Decision Support System:Predicting lightning threat utilizing integrated data sources, *Conference on Meteorological Applications of Lightning Data 8-14 January, San Diego, California.*

Dixon, M and G. Wiener, 1993: TITAN: Thunderstorm Identification, Tracking And Nowcasting, *J. Atmos. Tech*, **10**, 785-797.

Ebert, B., 2005: Verification of Forecasts, *WWRP Nowcasting Training Workshop, 28 November-9 December, Pretoria, Republic of South Africa*.

Gelb, A., 1974: **Applied Optimal Estimation**, MIT Press, pp. 374.

Georgia High School Association (GHSA), 2006: Lightning Detector Requirements, http://www.ghsa.net/?q=node/1.

Gin, R.A.A. and C.A.A. Beneti, 2004: Cloud-to-ground lightning flash density in the south and southeastern of Brazil: 1999-2003, *Fourth EMS Annual Meeting 26 – 30 September, Nice, France.*

Hodanish, S., 2006: Colorado Lightning Resource Page, *http://www.crh.noaa.gov/pub/ltg.php.*

Hogan, R.J., A.J. Illingworth, and E.P. Krider, 2002: Polarimetric Radar Observations of storm Electrification and Lightning, *Second European Conference on Radar Meteorology, 18-22 November, Delft Netherlands*.

Johnson, J.T., P.L. MacKeen, A. Witt, E.D. Mitchell, G.J. Stumpf, M.D. Eilts, K.W. Thomas, 1998*:* The Storm Cell Identification and Tracking Algorithm: An Enhanced WSR-88D Algorithm, *Weather and Forecasting*, **13**, 263-276.

Lund, N.R., D.R. MacGorman, W.D. Rust, T.J. Schuur, P.R. Krehbiel, W. Rison, T. Hamlin, J.M. Straka, and M.I. Biggerstaff, 2008: Relationship between lightning location and polarimetric radar signatures in an MCS, *Third Conference on Meteorological Applications of Lightning Data 21-24 January, New Orleans, Louisiana.*

McFarquhar, G.M., M.S. Timlin, R.M. Rauber, B.F. Jewett, J.A. Grim, A.M. Smith, and D.P. Jorgensen, 2005: Observations of the Horizontal and Vertical Variability of Cloud Hydrometeors in Stratiform Regions behind Bow Echoes: Implications for Mesoscale Models, *11th Conference on Mesoscale Processes, 22-28 October, Albuquerque, NM*.

Nelson, S., V. Adams, D. Selove, 1998: Lightning-Associated Deaths -- United States, 1980-1995, *MMWR*, **47**, 391-394.

Orville, R.E. and G.R. Huffines, 2001: Cloud to ground lightning in the United States: NLDN results in the first decade, 1989-1998, *Mon. Wea. Rev.*, **129**, 1760-1776.

Passarelli, R., 2005: Personal Communication – Discussion as to how graduate students would take a Tesla coil into refrigerator, blow on it and observe the creation of ice crystals, *32nd Conference on Radar Meteorology, 22-28 October, Albuquerque, NM.*

Rinehart, R.E., 1991: **Radar for Meteorologists Second Edition**, Knight Printing Company, Fargo, North Dakota, 334.

Vincent, B.R, L.D. Carey, D. Schneider, K. Keeter, and R. Gonski, 2003: Using WSR-88D reflectivity data for the prediction of cloud-to-ground lightning: A North Carolina study. *Nat. Wea. Digest*, **27**, 35-44.

Vivekanandan, J., D. S. Zrnic, S. M. Ellis, R. Oye, A. V. Ryzhkov, and J. Straka, 1999: Cloud microphysics retrieval using S-band dual-polarization radar measurements. *Bull. Amer. Meteor. Soc.,* **80,** 381–388.

Wolf, P., 2007: Anticipating the Initiation, Cessation, and Frequency of Cloud-to-Ground Lightning, Utilizing WSR-88D Reflectivity Data, National Weather Association, *http://www.nwas.org/ej/2007/2007.php.*

Wang, Z.,2007: ttp://www.weather.gov/code88d/code_b10.html

Zajac, B.A. and S.A. Rutledge, 2001: Cloud to ground lightning activity in the contiguous United States from 1995 to 1999, *Mon. Wea. Rev.*, **129**, 999-1019.

Zrnić, D.S., 2007: Polarimetric upgrade of the WSR-88D (NEXRAD) network, *33rd Conference on Radar Meteorology 6–10 August 2007, Cairns, Queensland.*