Evaluation of a Lightning Jump Algorithm with High Resolution Storm Reports

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ABSTRACT

Numerous studies have shown a correlation between rapid increases in lightning activity and the occurrence of severe weather at the surface. The skill of an automated algorithm that detects these rapid increases in lightning, or lightning jumps, was evaluated for 8 different cases in this study using high-resolution storm reports. A completely automated algorithm was used to identify and track storm cells in three domains: central Oklahoma, northern Alabama, and Washington D.C. Multiple storm attributes including total lightning were attributed to each tracked storm in 1-minute intervals. Lightning jumps with each of the 8 cases were then verified using high resolution storm reports collected during the Severe Hazards Analysis and Verification Experiment (SHAVE). These reports offered much better spatial resolution than NCDC *Storm Data*, and produced a more accurate view of hail and wind evolution or "severe storm periods" at the surface. For the 8 cases examined the algorithm produced an average lead time of 0 minutes when using SHAVE data for verification. Verification statistics were slightly better when using NWS storm reports though not nearly as good as that noted in previous studies.

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1. INTRODUCTION

Electrification in a storm occurs in the mixed phase region of a cloud where ice crystals, graupel, and supercooled liquid water droplets interact and collide. As collisions between large ice (e.g. graupel) and smaller ice crystals occur in the presence of supercooled liquid water, charge is transferred between the particles. (e.g. Takahashi 1978). As the particles are separated by both gravity and storm kinematics large scale charge separation occurs to form an electric field within the storm. When the field reaches a sufficient breakdown magnitude lightning is the result.

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There have been many studies linking the total lightning flash rate with storm microphysics and dynamics. Carey and Rutledge (1996,2000) and Petersen et al. (2005) showed that total lightning production in a storm is correlated to the total precipitation ice mass. Deierling et al. (2006) analyzed 11 different thunderstorms of varying storm types and regions, revealing a correlation between the vertical flux of ice and total lightning (cloud to ground and intracloud) flash rates. The kinematics of a hail producing thunderstorm were examined by Emersic et al. (2011) using phased array radar. They found rapidly increasing flash rates can act as indicators of sudden changes in updraft mass flux through the electrically active mixed-phase region. Therefore a stronger, more voluminous updraft has the potential to produce more lightning.

Severe weather at the ground is also inherently tied to storm and updraft strength. Hail growth requires an environment containing supercooled water droplets and sufficient vertical velocities to suspend the hailstones in the subfreezing cloud layer. Williams et al. (1999) found vertical velocities of at least 29 m s^{-1} were necessary to suspend hail of 0.75 inches (severe hail criteria prior to 2009). For hail sizes of the current severe threshold of 1 inch to remain suspended larger vertical velocities would be necessary. Severe winds (>50 knots) at the surface are often caused by downbursts that form due to precipitation loading of graupel, hail, and water droplets. When this dense precipitation mass begins to descend, cooling occurs due to evaporation and melting. The intensity of a downdraft or downburst may be more affected by ice than liquid (Srivastava 1987). A stronger updraft would be able to better "load" the eventual downdraft with graupel and hail and increase the potential for severe winds at the surface.

While it is well understood that severe weather is closely related to updraft strength, retrieving in-situ measurement of updraft velocities within a thunderstorm is not practical. The relationship between total lightning and updraft size and strength and associated severe weather has therefore been a topic of much research. Goodman et al. (1988) examined the lightning activity in a storm in Alabama and found an increase in lightning activity as the updraft neared its peak intensity, followed by a decrease in the flash rate as the storm collapsed and produced a wet microburst. A tornadic supercell in Oklahoma examined by MacGorman et al. (1989) was found to have increases in lightning (primarily intracloud) activity prior to peaks in shear within the mesocyclone. Williams et al. (1999) studied thunderstorms (severe and non-severe) in central Florida revealing a fairly consistent pattern of total lightning increases prior to severe weather of all categories (hail, wind and tornadoes).

With the general pattern of increases in total lightning flash rates prior to severe weather occurrence established, the possibility of using lightning trends as a warning tool has drawn interest. Gatlin (2006) established a methodology for testing a lightning jump algorithm against severe storm reports. A threshold of one standard deviation of the average rate of change of total lightning flash rate over time was used to first define a lightning jump. The primary interest of this study was tornadic storms, but non-tornadic severe storms were incorporated as well. Using a 5-minute flash rate moving jump threshold yielded a probability of detection (POD) of 73.6%, and a false alarm rate (FAR) of 45.1%.

Shultz et al. (2009) expanded on Gatlin (2006) by greatly increasing the sample size to include a wider variety of storm types. Additionally a variety of thresholds were used to define a lightning jump. Algorithms tested included one, two, and three standard deviation (σ, 2σ, 3σ) thresholds. An algorithm based on climatologically observed differences in flash rates between severe and nonsevere storms was also tested. The 2σ algorithm performed the best with a Probability of Detection (POD)=87% and False Alarm Rate (FAR)=33% for a 45-minute warning period; this met or exceeded the current NWS national averages for verification of a severe warning. Shultz et al (2011) tested the performance of the 2σ algorithm on a larger data set and compared it with only cloud to ground (CG) lightning. A decreased POD and increased FAR were found when using CG data only, suggesting total lightning trends are a better indicator of storm severity than CG trends alone.

Both the Gatlin and Shultz studies used NCDC *Storm Data* to verify lightning jumps. While the reports in *Storm Data* are the most comprehensive national dataset available, they vary greatly in spatial and temporal density from storm to storm. This can make verification of severe weather difficult and uneven. The goal of this study is to determine if the performance of the 2σ lightning jump algorithm differs when using high-resolution storm report data instead of NCDC *Storm Data*.

2. METHODOLOGY

2.1 High Resolution Reports

High-resolution storm reports used in this study are from the Severe Hazards Analysis and Verification Experiment (SHAVE) conducted in association with the National Severe Storms Laboratory. SHAVE reports of hail and wind damage are gathered through phone calls made to locations along or near a potentially severe storm's path immediately following a storm passage (Ortega et al. 2009). For the storms investigated in this study, the reports offer superior spatial and temporal resolution to *Storm Data*, (Figure 1).

Figure 1. NWS reports (left) and SHAVE reports (right) for a severe thunderstorm that moved across Harford County, MD on 4 June 2010. The area covered by SHAVE reports is overlaid on both images. The NWS reports missed almost the entire first half of hail fall when compared to SHAVE data.

2.2 Cases

Events were chosen based on two criteria. (1), the storm had to remain within the 3D range (125 km) of the Lightning Mapping Array for the entire period in question. (2), SHAVE reports had to be available near storm initiation. This was done for verification purposes to ensure periods of storm severity were not missed. Cases with the highest density of reports were selected.

2.3 Radar data

Archived Level-II radar data was obtained from NCDC for 5-8 WSR-88D radar sites surrounding each Lightning Mapping Array network. The radar data was then merged with the RUC Near Storm Environment (NSE) data using the Warning Decision Support System-II (WDSS-II) software (Lakshmanan et al 2007). The NSE data combined with the radar data created a multitude of products such as Maximum Estimated Size of Hail (MESH), Reflectivity at isothermal levels, and Reflectivity at Lowest Altitude.

2.4 Lightning Data

Total lightning data from the 3D Lightning Mapping Array (LMA) networks centered in Oklahoma, Alabama, and Washington D.C. was used for this study. These networks are each comprised of 10-12 stations that detect Very High Frequency (VHF) radiation points emitted during a lightning discharge. A WDSS-II algorithm was then used to group these points in time and space to determine individual flashes. For this project a minimum of 10 VHF points was used to determine a flash in order to reduce background noise.

2.5 Cell Tracking Algorithm

Automated cell identification and tracking was accomplished through WDSS-II using a K-means clustering and segmotion methodology similar to Hobson et al. (2012), originally developed and described in Lakshmanan et al. (2003, 2009). Storm cell clusters were identified and tracked at Reflectivity at -10C, which was typically a stable height for tracking with fewer mergers and dropped tracks than low-level or composite reflectivity. Storm features from multiple algorithms were associated with each cell (MESH, Max Reflectivity, lightning flash rate). See *Appendix* for additional details on the algorithms and procedures. The algorithm performed well on tracking discrete cells but struggled in cases involving cell mergers/splits. This study incorporates only storm cells that did not undergo a merger or split such that variations in lightning flash rates should be a direct reflection of the storm microphysics and kinematics. This reduced the number of cases to the final number of 8.

2.6 Lightning Jump Threshold

The 2σ lightning jump algorithm developed by Schultz et al. (2009) was used to determine a lightning jump for all cases in this study. The 1-minute flash rate is smoothed slightly by calculating an average flash rate every 2-minutes. A standard deviation calculation is then calculated for the five most recent periods (10 minutes total) of flash rate, not including the period of interest. When the change in flash rate exceeds 2 times the standard deviation of the previous 10-minute period a lightning jump occurs. A minimum threshold of 10 flashes min^{-1} is applied to the 2σ algorithm to eliminate smaller jumps associated with nonsevere convection.

2.7 Obtaining Report Times

The final step of data preparation was to approximate times of SHAVE reports. Since SHAVE reports are obtained through phone calls placed after storms have passed, many of the recorded times may not accurately reflect when the severe weather was actually occurring. To provide a best estimate of severe weather occurrence, reports were overlaid with Reflectivity at Lowest Altitude and analyzed using WDSS-II. The maximum sized hail report within the 40 dBZ contour of the storm was recorded in 5 minute intervals. This was taken to be the maximum hail occurring at the surface during that time period.

2.8 Lightning Jump Warning Length and Verification

For lightning jump verification a 30 minute "warning" was issued for the period immediately following a jump. A hit occurred if severe weather was reported within the warning period. To avoid inflation of detection probabilities, only one hit was allowed per jump. A false alarm occurred if no severe weather was reported within the 30 minute period. If the jump occurred after the first report of severe weather, it was recorded as a miss. Given that only severe cases were considered in this study there were no correct nulls. Lead time was also computed for the first occurrence of a jump, determined as the time between first jump and first severe report. Positive lead time was recorded for hits and negative lead time was recorded for misses. Subsequent jumps were not scored but were analyzed to see if the storm remained severe after the jump.

3. RESULTS

Each of the 8 cases investigated are included here. The performance of the algorithm against SHAVE reports will be discussed.

1) 10 June 2008

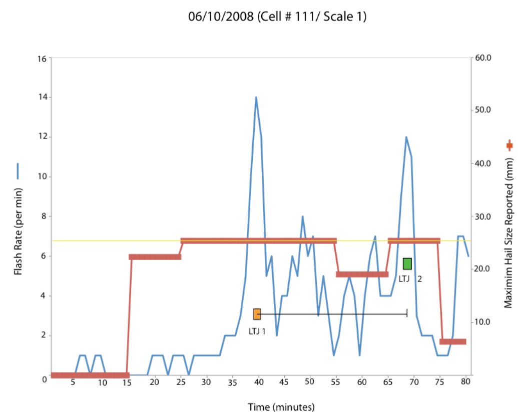

Figure 2. Total lightning flash rate and maximum hail size reported (SHAVE) on 06/10/2008. Lightning jumps are labeled (boxes) along with the 30 minutes warning period used for verification of the initial jump. Thin yellow line represents severe hail threshold (25.4 mm).

(Fig 2) A multicellular storm tracked across far northern Virginia within the D.C. LMA region on 10 June 2008. The storm cell was identified by the storm tracking algorithm at 1845 UTC. The flash rate during the first half hour was never greater than 1 flash per minute. However, the storm began producing marginally severe hail (25.4 mm) at 1910 UTC 14 minutes prior to the first lightning jump. This resulted in -14 minutes of lead time. A second jump occurred at 1953 UTC while the storm was still producing 25.4 mm hail. The storm quickly weakened following the second jump and dropped below severe threshold at 2000 UTC.

2) 16 July 2009

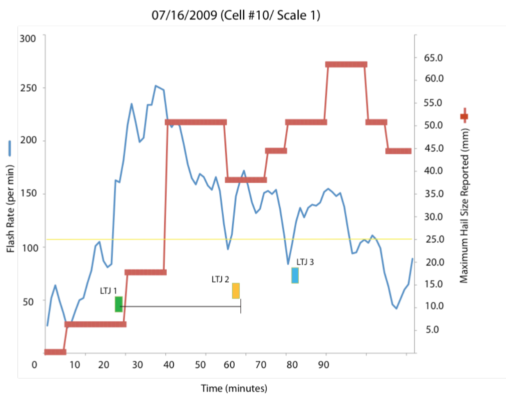

Figure 3. Same as Fig 2 for 07/16/2009.

(Fig 3) A supercell that tracked across the Oklahoma City metro on 16 July 2009, producing hail over 50.8 mm (2 inches) in size. Cell tracking began at 2055 UTC during rapid growth of the storm. The first lightning jump occurred at 2111 UTC during a period of 6.35 mm hail, well below severe limits. The first report of severe weather was at 2125 UTC, when 50.8 mm hail was reported. A hit and positive lead time of 14 minutes were recorded for the initial jump. Two subsequent jumps occurred with this storm, one at 2142 UTC and the next at 2157 UTC. The storm remained severe through this period. The peak flash rate (252 flashes min^{-1}) occurred at 2121 UTC, 4 minutes prior to the first severe report.

3) 4 June 2010

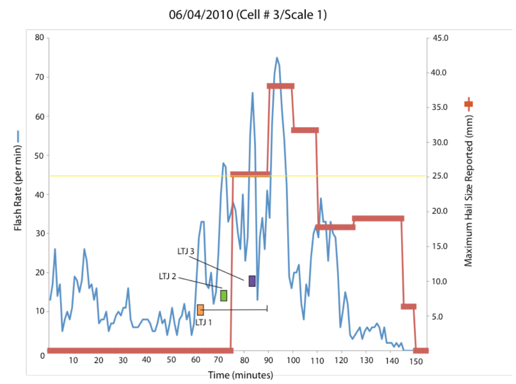

Figure 4. Same as Fig 2 for 06/04/2010.

(Fig 4) A multicellular storm tracked ESE across Harford County, MD within the D.C. LMA region on 4 June 2010. Cell tracking began at 2002 UTC well in advance of any lightning jumps or severe weather. The first lightning jump occurred at 2103 UTC, followed 14 minutes later by the first severe hail report at 2117 UTC. Subsequent jumps occurred at 2113 UTC and 2125 UTC while the storm remained severe. The peak in flash rate (about 75 flashes min^{-1}) occurred during the period of largest hail (38.1 mm).

4) 22 June 2010

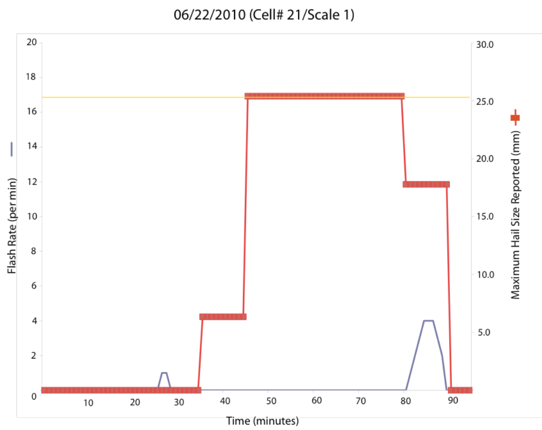

Figure 5. Same as Fig 2 for 06/22/2010.

(Fig 5) A single-celled storm tracked across central Virginia within the D.C. LMA on 22 June 2010. Cell tracking began at 2241 UTC with severe hail first reported 45 minutes later at 2326 UTC, and the storm remained severe for another 35 minutes until 0001 UTC producing hail at least 25 mm in size. This storm was unique for the set included in this study, producing little to no lighting during its lifetime and no jumps were recorded. A maximum flash rate of 4 flashes min^{-1} occurred for only a brief time between 0005 and 0008 UTC after severe hail had ended. This case was a miss for the initial jump.

5) 14 June 2011

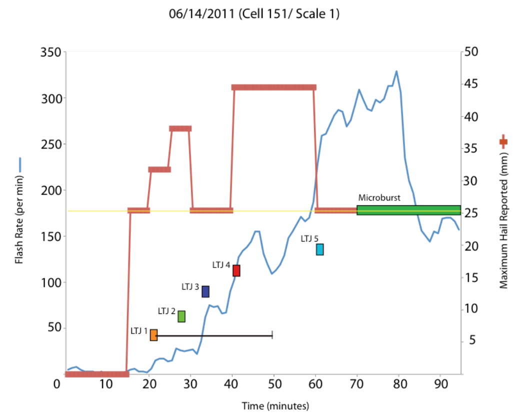

Figure 6. Same as Fig 2 for 06/14/2011. Green bar represents the time the storm produced a microburst and subsequent wind damage.

(Fig 6) A supercell storm tracked across Grady, McClain, and Cleveland counties in central Oklahoma on 14 June 2011. This storm produced 25.4–8.1 mm (1–1.5 inch) hail across the region as well as a microburst with winds of at least 35–40 m s^{-1} reported in Norman, OK. Cell tracking began at 2314 UTC and first report of severe hail occurred shortly thereafter at 2329 UTC. A lightning jump did not occur with this storm cell until 2335 UTC, resulting as a miss with -6 minutes of lead time. Four subsequent jumps occurred at 2341 UTC, 2347 UTC, 2354 UTC, and 0013 UTC while the storm remained severe. The peak in flash rate (329 flashes min^{-1}) occurred at 0031 UTC, about 10 minutes after the microburst first impacted the surface.

6) 3 August 2011

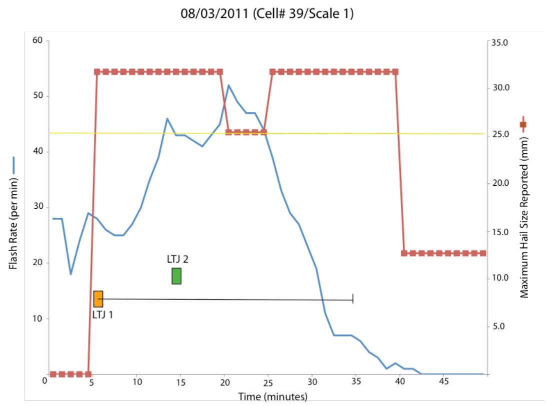

Figure 7. Same as Fig 2 for 08/03/2011.

(Fig 7) A single-celled storm tracked across Oklahoma City on 3 August 2011. Cell tracking began at 2129 UTC, rapid growth of the storm occurred shortly thereafter. At 2134 both the first lightning jump occurred and severe hail occurred, scoring as a hit with 0 minutes of lead time. At 2143 UTC a second lightning jump occurred while the storm maintained severity. No additional jumps occurred and the storm dropped below severe limits at 2209 UTC.

7) 12 August 2011

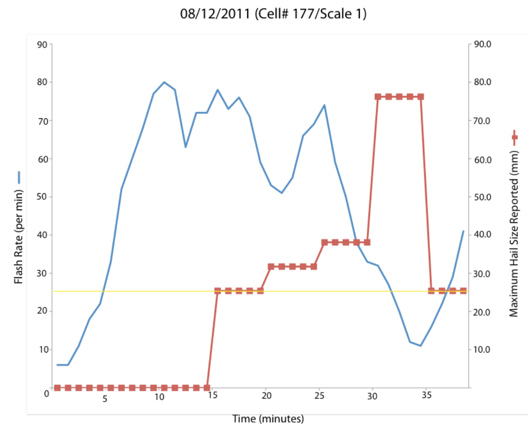

Figure 8. Same as Fig 2 for 08/12/2011.

(Fig 8) A single-celled storm moved across eastern Cleveland county into western Pottawatomie county in central Oklahoma on 12 August 2011. The cell was first detected by the tracking algorithm at 2239 UTC. The first severe hail of at least 25.4 was recorded at 2254 UTC. Even though this storm produced a peak flash rate of 80 flashes min^{-1} at 2249 UTC, no lightning jumps occurred during its lifetime. This peak occurred before any hail was occurring, and the maximum hail size of 76.2 mm (3 inches) occurred when the flash rate had dropped to 10 flashes min^{-1}. This case was therefore a miss for the initial jump.

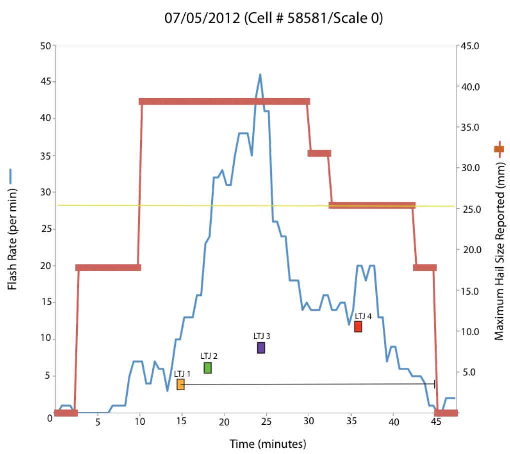

Figure 10. Same as Fig 3 except for 07/05/2012.

8) 5 July 2012

(Fig 9) A multicellular storm quickly developed over Lawrence county in southern Tennessee and tracked SSW across the North Alabama LMA. Cell tracking began at 2045 UTC. At 2050 UTC the storm produced 17.78 mm hail with severe hail of 38.1 mm recorded at 2105 UTC. The first lightning jump occurred at 2114 UTC, 9 minutes after severe hail. Subsequent jumps occurred at 2120, 2133, and 2156 UTC while the storm was still severe.

3.1 *SHAVE vs. NWS Reports*

The results using SHAVE data for the 8 cases above are included in Table 1. The algorithm's performance was also verified using NWS reports for the same 8 cases (Table 2). Using SHAVE data for verification produces an overall Probability of Detection (POD)= 37.5%, False Alarm Rate (FAR)=0%, and Critical Success Index (CSI)= 37.5% for the data set. Using *Storm Data* produces a POD=57.1%, FAR=33.3%, and CSI =33.3%. Average lead time was 0 minutes using SHAVE data and 8.4 minutes using NWS reports.

SHAVE Case	Cell #	Region	Hit	False Alarm	Miss	Lead Time (minutes)
06/10/08	111	DC			1	-14
07/16/09	10	OK	1			14
06/04/10	3	DC	1			14
06/22/10	21	DC			1	No jump
06/14/11	151	OK			1	-6
08/03/11	39	OK	1			0
08/12/11	177	OK			1	No jump
07/05/12	58581	AL			1	-9

Table 1. Verification of lightning jump algorithm using SHAVE reports only.

NWS Case	Cell #	Region	Hit	False Alarm	Miss	Lead Time (minutes)
06/10/08	111	DC			1	-19
07/16/09	10	OK	1			23
06/04/10	3	DC	1			25
06/22/10	21	DC			1	No jump
06/14/11	151	OK		1		-
08/03/11	39	OK	1			2
08/12/11	177	OK			1	No jump
07/05/12	58581	AL	1			11

Table 2. Verification of lightning jump algorithm using NWS reports only.

4. DISCUSSION

Comparing the results of the two sets, the SHAVE reports resulted in worse verification scores for the lightning jump than using NWS reports. This is primarily due to earlier report times of severe weather in the SHAVE data set. On average SHAVE reports occurred 16 minutes earlier than times of first severe for NWS reports. Earlier report times led to less lead time for the jumps and more misses overall.

The 14 June 2011 supercell storm is an excellent example of how the differences between the two data sets can affect the results. For this case the first severe SHAVE report was 44 minutes earlier than the first severe NWS report. While the lightning jump was a miss using the SHAVE data set, the 44 minute delay resulted in a false alarm when verifying the jump using NWS reports. Another difference occurred when scoring the 5 July 2012 multicell storm. The initial lightning jump occurred after the storm was already severe using SHAVE reports, but the jump occurred prior to the first NWS report. This resulted in a miss for SHAVE but a hit for NWS.

5. CONCLUSIONS

Overall the lightning jump did not perform as well for either verification data set as the results from Schultz et al. (2009/2011). The small sample size of this study limits the statistical significance, however, many points can still be made.

(1)

SHAVE reports offer a much more accurate view into the evolution of a storm. Having reports available in nearly a continuous path gives more confidence as to severe storm periods. The use of SHAVE data produced different lightning jump verification results as compared to using NWS reports alone.

(2)

Cases that involved cell merger/splits or linear convective systems could not be used as the automated tracking algorithm could not handle these situations. If this lightning jump algorithm were to be put into place operationally these types of issues would need to be resolved.

(3)

The threshold used for lightning jumps may need further adjustments as the algorithm did not perform well on storms that produced very little lightning. This was also found to be the case in Shultz et al (2009/2011).

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APPENDIX

Included here are the commands that were run using the WDSS-II software and brief comments regarding their function.

1)conversion process for radar data

>> ldm2netcdf -i `pwd`/radar/KFDR -o `pwd`/KFDR -a -1 -s KFDR -p KFDR

-Converts NCDC radar data from ldm format to net cdf

>> gribToNetcdf -i `pwd`/model -o `pwd`/RUC -a -1 -k -p ruc2

-Converts grib files to net cdf

>>nse -i `pwd`/RUC/code_index.xml -o `pwd`/NSE -D -

-reads in model data and computes a number of parameters important for severe thunderstorms (CAPE, shear, etc)

>>w2qcnn -i `pwd`/code_index.xml -o /data/terrain/KFDR.nc -s KFDR -R 0.25x0.5x460

-quality control neural net

>>cp -r ../NSE/SoundingTable/KFDR SoundingTable

>>dealias2d -i `pwd`/code_index.xml -o `pwd` -S SoundingTable -R KFDR

-dealias radar velocity field

6)index, then:

>>w2circ -i `pwd`/code_index.xml -o `pwd` -a -w -z ReflectivityQC -Z 40 -t -D -c -L "0:3:0:7.5:AGL 3:6:0:90:AGL" -V "0.5 250 920" -g /data/terrain/KFDR.nc -G KFDR -S -s -j -F -b 5

- computes azimuthal shear using linear least square technique

>>makeMissingRadar -o `pwd`/KFAKE -N 1 -b YYYYMMDD-hhmmss -e YYYYMMDD-hhmmss

-For merger so that radar data is written out in consistent 1-minute increments

>>replaceIndex -i "`pwd`/KFDR/code_index.xml `pwd`/KFWS/code_index.xml `pwd`/KICT/code_index.xml `pwd`/KINX/code_index.xml `pwd`/KSRX/code_index.xml `pwd`/KTLX/code_index.xml `pwd`/NSE/code_index.xml `pwd`/KFAKE/code_index.xml" -o `pwd`/merger_index.xml

w2merger -i `pwd`/merger_index.xml -o `pwd`/multi -I ReflectivityQC -t "38.0 -103.0 21" -b "31 -91 0" -s "0.01 0.01 1" -g 4 -e 60 -R 300 -C 4 -a "Composite LayerAverage VIL HDA"

Took in individual radar data and merged them together using inverse squared weighting scheme on distance, only used radar data within 300 km of radar site, and ran algorithms to compute fields (-a)

DCLMA: -t "40.9 -80.1 25" -b "37 -74.0 0"
FLLMA: -t "30.4 -82.8 25" -b "26.5 -78.6 0"

NALMA: -t "36.6 -89.0 25" -b "32.3 -83.9 0"

Lightning data (ASCII) files were put into a raw directory

>w2lma_ingest -i `pwd`/raw -o `pwd`/ltg

>w2lmaflash -i `pwd`/ltg/code_index.xml -o `pwd`/flashdata -I TotalLightning:LMA -N 10 -Q 7 -t "37.5 -99.85 25" -b "33.5 -95.5 0" -s "0.01 0.01 5" -p "1 2" -e 1 --verbose

DCLMA: -t "40.9 -80.1 25" -b "37 -74.0 0"
FLLMA: -t "30.4 -82.8 25" -b "26.5 -78.6 0"
NALMA: -t "36.6 -89.0 25" -b "32.3 -83.9 0"

-Created lightning products used in later cell tracking.

>>replaceIndex -i "`pwd`/multi/code_index.xml `pwd`/OKLMA/flashdata/code_index.xml" -o master_index.xml

>>w2segmotionll -i `pwd`/master_index.xml -o /data/pware/20110614/jump_dbz10 -f "VIL VILMA MESH MergedReflectivityQCComposite Reflectivity_-10C FlashExtentDensity_001minComposite FlashInitiationDensity_001minComposite InNetworkRange" -A NoSuchProduct -T Reflectivity_-10C -d "20 50 5 -1 0" -X /home/pware/kmeans_jump.xml -p "100,200,400,600,800,1000:1:0.0,0.0,0.0,0.0,0.0,0.3" -k "threshold:20:50,percent:90:5:0.33:5" --verbose -F 30000000"

-A k-means technique used to segment images and create trackable clusters, tracing field was reflectivity at -10C. Software allows other variables to be tracked (-f) and different calculations can be performed (for lightning jump). Definitions for these calculation listed in xml file (-X)