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Jacob W. Smith
Iowa State University

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Analysis of the Rear Flank Gust Front Surge's Role on the Path and Intensity of the May 20th, 2013 Moore, OK Tornado

Jacob W. Smith

Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa

Dr. James Aanstoos – Mentor

Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa

ABSTRACT

On May 20th, 2013, Mother Nature unleashed its wrath on Oklahoma City, Newcastle, and Moore, Oklahoma with a violent and long-track EF-5 tornado. The University of Oklahoma (OU) was prepared with their Advanced Radar Research Center’s PX-1000 transportable, polarimetric, X-band weather radar (Kurdzo et al. 2015). The PX-1000 took twenty second scans of this storm at a high resolution with its only limitation of keeping the beam at a fixed elevation of 2.6°, below 500m, to achieve the fastest scan times possible. The radar observed a number of small scale features that are typically found in a tornado producing cyclic supercell. This includes eight rear flank gust front surges, six debris ejections and multiple shifts in path. The rear flank down draft is one of the key components in tightening a supercell’s circulation and inducing tornadogenesis. With this in mind, is it possible that surges in the rear flank down draft could influence some of the characteristics of the tornado? We will investigate this question throughout this paper, specifically, do rear flank gust front surges (RFGFS) have any influence on the differential velocity, speed, or direction of the tornado? During our investigation we also stumbled upon some data that suggests that the RFGFS could have also influenced the damage intensity and spread in some regions. This will be discussed in a supplemental material section on page 18.

1. Introduction and Background

On May 20th, 2013 at approximately 2:56 pm CDT (1956 UTC) storm chasers reported a rapidly developing funnel cloud touching down in Newcastle, OK. Growing quickly, this destructive tornado produced EF-4 damage in the early stages of its life in Newcastle, OK continuing to grow as it moved into Oklahoma City. Evidence of a hook echo began to appear on reflectivity 14 minutes prior to tornadogenesis on Oklahoma City’s KTLX radar. After tornadogenesis, this powerful supercell displayed impressive radar features including a hook echo exceeding 60dBZ, inbound/outbound radial velocities exceeding 60m/s as well as Correlation Coefficient values as low as 0.21 in the debris ball at its most damaging point.
In all the tornado’s max width was 1737 m, just under 40% of all structures that received EF-1 damage or greater were completely destroyed (EF-3+), and once the 39 minute tornado finally roped out 24 lives were lost and 200+ were injured (Burgess et al. 2014).

Throughout the tornado outbreak the University of Oklahoma was operating a mobile PX-1000 polarimetric X-band weather radar that was operating at 100-W peak power on each channel. It has a 1.8-m-diameter parabolic dish resulting in a 1.8° azimuthal resolution at 9.55 GHz. The radar was kept about 11 km away from the storm because there was lower sensitivity anywhere within 10.3 km of the radar. The supercell did enter this 10.3 km boundary, which would present a problem with weaker echoes, but it was producing strong echoes while in this region and the data is still valid for analysis. (Kurdzo et al. 2015). During the event, the PX-1000 weather radar was operating at a 2.6° elevation while taking new scans every 20 seconds. To achieve such rapid scan rates the PX-1000 beam height was held at a constant elevation. To achieve volumetric analysis with the PX-1000 researchers would have had to scan multiple elevations. This process would greatly increase the amount of time between each scan.

The May 20th, 2013 supercell that produced the Moore tornado underwent cycles of intensification and weakening throughout its lifetime making it a cyclic supercell. Cyclic supercells are known for producing families of tornadoes (Dowell and Bluestein 2002), but in the case of May 20th, 2013 it was one monstrous tornado. Evidence of a cyclic nature with this storm was observed on multiple occasions through the tornado’s life.
Observations from the PX-1000 radar revealed many characteristics of the storm that could not be seen with a WSR-88D in storm mode. Such characteristics include six debris ejections, eight rear flank gust front surges (RFGFSs), as well as small scale track shifts throughout the tornado’s lifetime (Kurdzo et al. 2015).

While RFGFSs and debris ejections have been observed, more research needs to be done to understand these phenomena. May 24th, 2011 a rapid scan, polarimetirc, Doppler radar observed multiple violent tornados near El Reno, OK. When preforming the data analysis (Houser et al. 2015) observed multiple momentum surges in the Rear Flank Gust Front (RFGF). The same phenomena was observed May 18th, 2010 in Durmas, Texas during the VORTEX2 project. (Skinner et al. 2014) discussed their observations of momentum surges within the broad-scale rear-flank outflow. What sets the May 20th, 2013 tornado apart from the rest of these cases is the path it took throughout its lifetime. As previously mentioned, eight RFGFSs were observed during this cyclic supercell’s lifetime. Since the tornado was moving over such a densely urbanized area, six of those RFGFSs produced debris ejections that were visible from the PX-1000 radar.

Prior studies have looked at comparisons between RFGFSs and mesoscale structure as well as RFGFSs and ongoing tornadic debris (Kurdzo et al. 2015). It has become common knowledge in the tornado research field that rear flank down drafts are one of the driving mechanisms for tornadogenesis. What is still unknown is if the surges within the rear flank down draft can that have an effect on some of the characteristics of the tornado. Each RFGFS is unique in its own way with variations in surge intensity, the directions of the surge, and the duration of each surge. To learn more about how RFGFSs effected this tornado, we used the high quality data taken by OU to investigate links in the characteristics of the RFGFSs and any changes in the tornado’s intensity, movement, and direction.

2. Data and Methods

a. Data Selection

The data gathered from this project was given by a team led by Dr. Robert Palmer from the University of Oklahoma. Their team was in charge of the PX-1000 while it was observing the large and violent tornado. The radar of interest is a PX-1000 polarimetric X-band weather radar that was operating at 100-W peak power on each channel. It has a 1.8-m-diameter parabolic dish resulting in a 1.8° azimuthal resolution at 9.55 GHz. During this event, the radar was taking sector scans directed at the tornado for its entire lifetime. The radar was held at a fixed elevation of 2.6° throughout the storm’s lifetime (Kurdzo et al. 2015). There were 126 radar scans throughout the tornado’s 39 minute lifetime. The data begins at 19:50:07 UTC, just six minutes before tornadogenesis and was taking scans every 40 seconds until 19:52:26 UTC. Here the radar began to take faster scans and was now collecting new scan data about every 20 seconds. The PX-1000 continued to monitor the tornado throughout
its life time until 20:39:51 UTC, four minutes after the tornado lifted.

**b. Data Reader**

This case provided some unique data that needs a specially designed data reader to resolve it. A team of researchers at OU wrote a Matlab data reader program that takes in the radar data, processes it, and displays the data on a Cartesian coordinate system where both the X and Y axis are measured in kilometers. The program displays Reflectivity (dBZ), Radial Velocity, Correlation Coefficient (pHV), and Differential Reflectivity ($Z_{DR}$) on four separate figures. Along with these four figures, a tool bar is displayed for analysis purposes where you can zoom, move in the X and Y direction, as well as use data cursor that reads specific pixels to give exact data at any given point. With all of these features a thorough visual analysis can be executed along with numerical and statistical analysis.

**c. The Tornado’s Lifetime**

The tornado began its path of destruction just south of NW 32nd St in Newcastle, OK. The tornado then moved NE at about 23km/hr, as calculated with the KTLX radar, and did its first EF-4 damage. After crossing the Canadian river it began to shift its track to ENE as it continued its path of EF-3 damage with EF-4 damage mixed in. As the tornado crossed the intersection of S May ave and SW 149th St around 3:08pm (2008 UTC) the track again began to shift more East than North running almost parallel with SW 149th. Between S May ave and I-35 the tornado did some its most significant damage. It was around 3:15pm (2015 UTC) when the tornado caused its first EF-5 damage. After crossing Santa Fe Ave, the tornado again shifted its track this time shifting NW as it approached I-35. It was about 3:22pm (2022 UTC) as the tornado was racing NW at about 39km/hr when it dramatically changed direction and speed at SW 4th St and S Telephone Rd. The tornado began to slow down almost stop at one point, looped back around and began moving SE for about a kilometer before it resumed its previous heading just North of East. During the tornado’s shift in path it maintained it strength visually on radar with a 2.8km wide debris ball seen with correlation coefficient with a beam height of 220m provided by the KLTX radar. After the tornado shifted its path, it sped up from 30km/hr to 54km/hr maintaining a slightly thinner swath of EF-4 damage for the next 4.2km. As state by (Burgess et al. 2014) from this point on, the tornado was in low-density housing areas or in completely rural areas. One final home in the low-density housing area was rated EF-5.
The final structures that were damaged were on a farm along S. Air Depot Road. The tornado then dissipated in a tree line about 230m east-southeast of the farm at 3:35pm (2035 UTC).

d. Visual Analysis

The PX-1000 radar on site produced radar imagery about every 20s including reflectivity, differential reflectivity, velocity, and correlation coefficient. Thanks to analysis done by Kurdzo et al. 2015, we know how many RFGFSs occurred, their peak winds, the primary direction they were blowing, as well as when and how long they occurred. Using this information, radar imagery was gathered during the surges in an effort to better understand key radar features of the surges.

Other visuals used to aid in analysis include overlaying the position of the beginning of the RFGFS, which is when RFGFS initially reaches the tornado vortex, onto the damage intensity map found in figure 1. We also put arrows over each surge to indicate their primary direction. This was done to see if there are any suggestions that the RFGFSs could have played a role in the intensity of the damage produced by the tornado. This will be further discussed in the supplemental material section on page 18. To further investigate our question, adaptations of figure 5 in the paper by Kurdzo et al. 2015 were made. This figure displays the maximum EF-scale damage rating, differential velocity of the tornado vortex, as well as the direction of the tornado throughout its life. We took the four variables being analyzed and individually compared them to the event timeline, specifically with the start of the surges. This was done with the goal in mind of finding relationships between how the tornado changes during the start of each surge.

e. Numerical and Statistical Analysis

Numerical characteristics of the RFGFSs had been gathered previous to this study and include duration of the surge, maximum velocity of the surge, and its primary direction. Using the given radar data we were also able to put together a table of tornado data for every 20 seconds throughout its life. The data on the table included the maximum differential velocity of the tornado, the maximum EF-Scale damage rating as well as the speed and direction of the tornado. Using this data we were able to plot RFGFS occurrences next to the tornado data in an attempt to find correlations in changes in the tornado during the pass of a surge.
3. Results

a. Numerical Results

Is there a link in RFGFS occurrences and characteristics with changes in differential velocity, path direction, and speed of the tornado? To answer this question we chose a variable, for example, differential velocity. We then found a value of this variable 40 seconds before a surge and 40 seconds after for every surge. Then, the average and standard deviation of the change in differential velocity was recorded. We took data 40 seconds before and 40 seconds after the surge because that’s about when environmental conditions around the tornado changed. This process was repeated when analyzing forward ground speed as well as the change in direction of the tornado vortex. A table of data on each surge is available in appendix A.

b. Changes in Differential Velocity

In an attempt to understand the effect that RFGFSs could have on the differential velocity of the tornado we found the speed that the tornado was spinning before the surge and after the surge to compare the two. This method of analysis was used on each surge throughout the tornado’s lifetime. We found that during RFGFS 1, 3, and 8 the tornado winds increased, the most substantial magnitude increase was during the 3rd surge at 14.4 m/s and the least substantial increase was during the 1st surge at 0.59 m/s. During surges 2, 4, 5, 6, and 7 the tornado’s wind speeds decrease after the surge occurred. The most substantial wind decrease came during the 5th surge where the winds decreased by 25.38 m/s, which is about 56.8 mph within a minute and twenty seconds. The least substantial decrease in winds was during the 6th surge where the winds decreased by 2.55 m/s. The average change in the tornado’s winds before and after the surge occurred was -1.94 m/s and the standard deviation of the change is 12.21 m/s. The range of values that fall into 1 standard deviation are -14.15 m/s and 10.27 m/s. The surges that correlate to a change in differential velocity that falls into this range are surges 1, 2, 4, 6, 7, and 8. RFGFS 3 and 5 are the surges that fall out of range of one standard deviation.

c. Changes in Forward Ground Speed

To understand the effects the RFGFSs could have on the Forward Ground Speed (FGS) of the tornado we found the FGS of the tornado before and after the surge to compare the two. We found that during surges 3 and 6 the FGS of the tornado increases. The most substantial increase came from RFGFS 3 where the tornado increased its FGS by 3.93 m/s. During surges 1, 2, 4, 5, 7, and 8 the tornado’s FGS decreased. The most substantial decrease came during RFGFS 7 where the FGS decreased by 8.73 m/s. The average change in forward ground speed of the tornado during each surge is -2.13 m/s and the standard deviation is 4.32 m/s. This means the range of values that fall into one standard deviation are -6.45 m/s and 2.19 m/s. The RFGFSs that saw a change in FGS that falls into the range of one standard deviation are RFGFSs 1, 2, 4, 6, and 8. The surges that do not fall into this range are surges 3, 5, and 7.
d. Changes in Direction of the Vortex

Understanding how the RFGFSs could have affected the direction of the tornado’s movement is a little bit more complicated than the previous variables because of the units being measured. Measuring direction is obviously circular, so the methods for analyzing this variable slightly deviates from the previous two. The tornado experienced a positive shift, a shift to the right, in track during the first RFGFS. During the second RFGFS it experienced virtually no shift in track. During surges 3, 4, 5, 6, 7, and 8 the tornado shifted track in the negative direction, or to the left. The greatest change in direction occurred during RFGFS 6 where the tornado made its loop. If we exclude the loop, the greatest change came during RFGFS 5 of 44.6° to the left. The average change in direction is -26.93°. A significant change in tornado track will be considered any time the tornado changes ~22° or more. To put it into perspective, ~22° is the difference in direction between NE and ENE.

4. Discussion and Conclusions

a. Preface

The 2013 Moore, OK tornado was one of the first long track, deadly tornados to be observed by a rapid scan, high resolution radar. With that being said, the results of this analysis apply strictly to this case and this case only. If any general conclusions about RFGFSs role on tornado characteristics are to be made, analysis of many more cases must be done to achieve consistent results. Until then, the conclusions drawn in this paper will only suggest relationships, with the goal in mind to apply this analysis to other cases in hopes of finding consistent results.

b. Discussion of Results

In general when studying the changes in differential velocity during each surge, it was found that differential velocity slows at the start of the surge. The outliers from this norm were RFGFS 1, 3, and 8 where an increase in differential velocity occurs. This finding is particularly interesting because early in the project, the RFGFS occurrences were overlaid onto the damage scale map. What was found was that there were multiple spikes in damage intensity when the RFGFS occurred. This lead us to believe that when the RFGFSs occurred, they slammed into the tornado, increased its differential velocity and that could explain the spikes in damage intensity. We now know this is likely not the case because when the RFGFS occurs there’s either no real change in the differential velocity or rather it actually decreases. In a few cases the differential velocity continues on the trend it was previously on during the passing of a surge. But, during a majority of the surges the differential velocity slowed at the impact of a surge. What caused the spikes in EF-Scale damage during the surges will be discussed in the supplemental material section on page 18.

The results for the change in forward ground speed told a different story than the differential velocity. When the FGS of the tornado was plotted next to RFGFS occurrences a pattern became noticeable. Besides the few outliers, the FGS of the tornado seemed to decrease right when RFGFS 1, 2, 4, 5, 7, and 8 occurred. For a surges 2, 5, 7, and 8 the tornado was actually
accelerating when the surge occurred, but just as the surge occurs the tornado stops speeding up and quickly begins to slow down. A possible explanation as to why RFGFS 3 and 6 did not see this happen was because there were other dominating physical processes occurring. For example, during RFGFS 3 there was also a phenomena called the ‘southern surge’ occurring where an area of high reflectivity (~60 dBZ), high differential reflectivity (~5 dB), and low correlation coefficient (~0.9) broke off from the rear/forward-flank downdraft interface north of the tornado and surged southward along the RFGF at a speed of 29 m s\(^{-1}\) (Kurdzo et al. 2015). As soon as the data is available, it will be interesting to see if other similar cases will see similar results. Like the forward ground speed, a pattern could also be seen with RFGFS occurrences and changes in the direction of the tornado’s movement.

The direction of the tornado changed consistently after the first two RFGFSs occurred. There was a slight positive shift in direction during the first surge and no change during the second surge. After that, the tornado consistently shifted in the negative direction (to the left) when a RFGFS occurred. The tornado experienced significant shifts in track during RFGFS 3, 5, 6, and 8.

As stated earlier, the data points chosen to compare how the tornado’s characteristics might have changed with RFGFS occurrences were taken 40 seconds before the occurrence and 40 seconds after the occurrence. This time interval we feel will best illustrate how the tornado could have changed from the RFGFSs. There were not enough cases to do an accurate T test and find statistical significance, but if you look at the big picture of the results there is a pattern. The tornado’s differential velocity slows down during the majority of the RFGFSs. The speed of the tornado vortex slows during a majority of the surges. Lastly, the tornado tends to turn to the left during a gust front surge occurrence. Seeing results like this suggest that the RFGFS could be playing a role on how these characteristics of the tornado behave. The next question to ask is, what conditions were present during the RFGFS occurrences and could these occurrences be predicted? Specifically for this case, the supercell produced the tornado at 1956 UTC, but RFGFS occurrences didn’t begin until 2008:41 UTC. About 12 minutes elapsed before RFGFSs began occurring after tornadogenesis, meaning the first 1/3 of the tornado’s lifetime did not experience RFGFSs. This all occurred at the same time that the supercell was ingesting a small cell with light precipitation into the updraft region. When the first RFGFS occurs, the small cell has just about been completely ingested. When the updraft region finally clears and has access to warm moist air in the environment, the RFGFS occurrences immediately increase. This suggests for this case that the presences of a consistent uninterrupted updraft could be favorable for RFGFS-genesis.

Regarding RFGFS impact on tornado characteristics, the pattern found from the results does suggest that our hypothesis was wrong. The RFGFSs travel within the rear flank down draft through the cell until they reach the tornado vortex and begin to wrap back around the tornado. This means the
RFGFSs generally originated to the NW of the tornado vortex and moved southward along the RFD. They are then wrapped around the tornado vortex until they get below the radar scan and eventually hit the ground and dissipated. This process led us to originally believe that since the surges were flowing with the direction the tornado was spinning, the surges would strike the tornado vortex and increase the speed of the differential velocity of the tornado, increase the forward ground speed of the tornado and leave the direction unaffected. Analysis eventually proved that this thought process was incorrect because the differential velocity and forward ground speed tended to slow rather than speed up and the direction of the tornado consistently shifted to left at the start of a RFGFS.

c. Future Work

An idea for a future study could be using a technique that Dr. Leigh Orf from the University of Wisconsin has taken advantaged of to aid in understanding how tornados work. Using advanced modeling and a super computer out of the University of Illinois, Dr. Orf has a code where you can input environment data and it simulates the supercell and tornado of interest at an incredibly high resolution. Using this method on the May 20th 2013 Moore, OK tornado, could help us understand what was happening within the cell when these surges occurred. The next obvious task to be done with this research is to gather more data and cases so analysis can be done on many other storms. The more cases we have, the better we will understand RFGFSs impact on tornados.

d. Conclusions

In all, a great deal of information can be gathered from the given data. Strictly in the case of the May 20th 2013 tornado, the RFGFS may be impacting the tornado. Evidence suggests the impact of a RFGFS generally slows the differential velocity of the tornado, it slows the forward ground speed of the tornado, and turns it to the left. This information will be more scientifically relevant when more cases can be analyzed and a similar studies can be done. This will also allow for the opportunity to study the conditions present during the RFGFS occurrences. The findings of the study and other similar studies done in the future can be useful in understanding the different variables that impact tornados and alter their characteristics. The more we know about tornados and understand how they work, the easier they will be forecast. Increased forecasting abilities would allow us to create better warning systems and potentially save lives.

During the analysis, other interesting information was drawn from the data regarding the impact of RFGFS occurrences on the EF-Scale rating in the regions the surges occurred. Unexplained expansions in tornado damage in some of these regions were also present. This will be briefly discussed in the supplemental material section of the paper on page 18.

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Appendix

Appendix A: This table displays RFGFS characteristics in the left 5 columns. The remaining columns are information about how tornado characteristics changed during each surge.

<table>
<thead>
<tr>
<th>Gust Front Surges</th>
<th>Time (UTC)</th>
<th>Radar Estimated Time Duration (s)</th>
<th>Maximum Velocity of Surge (m/s)</th>
<th>Primary Direction of Surge (°)</th>
<th>EF Rating During Surge</th>
<th>Change in Differential Velocity Before/After (m/s)</th>
<th>Change in Forward Ground Speed of Tornado (m/s)</th>
<th>Change in Direction of Vortex Movement (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFGFS 1</td>
<td>2008:41 - 2010:01</td>
<td>80</td>
<td>18.1</td>
<td>116 (ESE)</td>
<td>EF-3 to EF-4</td>
<td>0.59</td>
<td>-2.04</td>
<td>7.8</td>
</tr>
<tr>
<td>RFGFS 2</td>
<td>2014:59 - 2018:38</td>
<td>219</td>
<td>13.4</td>
<td>206 (SSW)</td>
<td>EF-4</td>
<td>-5.65</td>
<td>-0.37</td>
<td>0</td>
</tr>
<tr>
<td>RFGFS 4</td>
<td>2019:58 - 2023:36</td>
<td>218</td>
<td>11.6</td>
<td>223 (SW)</td>
<td>EF-4</td>
<td>-2.58</td>
<td>-1.39</td>
<td>-16.7</td>
</tr>
<tr>
<td>RFGFS 5</td>
<td>2021:37 - 2026:55</td>
<td>317</td>
<td>18.7</td>
<td>75 (E)</td>
<td>EF-5</td>
<td>-25.38</td>
<td>-7.82</td>
<td>-44.6</td>
</tr>
<tr>
<td>RFGFS 6</td>
<td>2022:37 - 2026:55</td>
<td>257</td>
<td>26.4</td>
<td>184 (S)</td>
<td>EF-5 to EF-4</td>
<td>-2.55</td>
<td>1.64</td>
<td>-112.9</td>
</tr>
<tr>
<td>RFGFS 7</td>
<td>2027:15 - 2028:55</td>
<td>100</td>
<td>20.1</td>
<td>152 (SSE)</td>
<td>EF-3 to EF-4</td>
<td>-6.15</td>
<td>-8.73</td>
<td>-3.6</td>
</tr>
<tr>
<td>RFGFS 8</td>
<td>2031:14 - 2032:54</td>
<td>100</td>
<td>19</td>
<td>137 (SE)</td>
<td>EF-2 to EF-1</td>
<td>11.76</td>
<td>-2.27</td>
<td>-23.3</td>
</tr>
<tr>
<td>Average</td>
<td>X</td>
<td>178.875</td>
<td>17.6125</td>
<td>X</td>
<td>X</td>
<td>-1.94</td>
<td>-2.13125</td>
<td>-26.9375</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>X</td>
<td>86.23296933</td>
<td>4.732090296</td>
<td>X</td>
<td>X</td>
<td>12.21298372</td>
<td>4.318489939</td>
<td>38.39449133</td>
</tr>
</tbody>
</table>
Appendix B: This is an edited graphic from the National Weather Service’s damage survey of the May 20\textsuperscript{th} 2013 Moore, OK tornado. The black circles highlight the region where the RFGFS occurred.
Appendix C: This figure displays the differential velocity of the tornado throughout its lifetime alongside the event timeline. The rectangular boxes seen are located over an RFGFS start and expand up to the differential velocity of the tornado in an attempt to display how the differential velocity of the tornado changed with the start of an RFGFS. Adapted from Kurdzo et al. 2015 figure 5.

Appendix D: This figure displays the forward ground speed of the tornado throughout its lifetime alongside the event timeline. The rectangular boxes seen are located over an RFGFS start and expand up to the forward ground speed of the tornado in an attempt to display how the forward ground speed of the tornado changed with the start of an RFGFS. Adapted from Kurdzo et al. 2015 figure 5.
Appendix E: This figure displays the direction of the vortex movement throughout the tornado’s lifetime alongside the event timeline. The rectangular boxes seen are located over an RFGFS start and expand up to the direction of the vortex movement of the tornado in an attempt to display how the direction of the vortex movement changed with the start of an RFGFS. Adapted from Kurdzo et al. 2015 figure 5.

Appendix F: This figure displays the max EF-Scale damage rating throughout the tornado’s lifetime alongside the event timeline. The rectangular boxes seen are located over an RFGFS start and expand up to the max EF-Scale damage rating of the tornado in an attempt to display how the max EF-Scale damage rating with the start of an RFGFS. Adapted from Kurdzo et al. 2015 figure 5.
Appendix G: This is a sample picture of reflectivity (dBZ) at 2000:44 UTC. The purpose of this figure to show the area of light precipitation that is consumed by the cell in the beginning of its lifetime. Notice the area of light precipitation where the weak echo region of the storm should be.
Appendix H: This is a sample picture of reflectivity (dBZ) at 2016:59 UTC. The purpose of this figure to show the area of light precipitation being completely consumed by the cell. Notice how the updraft region of the cell is now clear of the region of light precipitation and a well-established weak echo is in place.
Appendix I: This figure shows the damage spread throughout the majority of the tornado’s lifetime. The circles indicate where an RFGFS occurs and the arrows show the primary direction of the surge. This figure is edited from the National Weather Service’s damage survey of the May 20th 2013 Moore, OK tornado.
Supplemental Material

While gathering and analyzing data for our hypothesis, a few other interesting features stuck out to us that did not directly relate to the hypothesis. For this reason, these features will be discussed in this section of the paper. The supplemental material section will include discussion about the RFGFSs potential impact to the EF-Scale’s intensity and spread.

a. RFGFSs and Damage

The idea that the RFGFS could have played a role on the intensity and spread of the damage throughout this tornado came from appendix B and F. In appendix F we see the max EF-Scale damage that occurred during the lifetime of the tornado and the event timeline with the start of the surges highlighted. During four of the surges we can see on this graph that the tornado’s damaging rating increases right as the surge occurred. Because of a smoothing feature you can’t see the 5th damage increase that does occur during the last RFGFS. In appendix B we can see where the RFGFS began to occur relative to what kind of damage was done over the region. The first feature that sticks out is the damage increase from EF-3 to EF-4 during surges 1, 7, and 8. It seems the damage increases around the same time these surges occur. This supported the original hypothesis because we thought the surges would increase the differential velocity of the tornado and increase the damage in that region. As discussed previously, the tornado actually began to spin slower when most of the surges occurred. The question then became, what is causing the short lived damage increase during surges 1, 7, and 8?

To answer this question we need to first understand how rear flank down drafts work. Rear flank down drafts originate in high elevations within the supercell and fall with precipitation. Eventually they will be wrapped around the majority circulation within the supercell and crash into the ground. They also often assist in tightening up circulations within the supercell and inducing tornadogenesis. To observe the surges in the rear flank down draft, radar data was downloaded for every frame so the images could be animated together and we looked at correlation coefficient. This was done so that we could observe when and where the RFGFSs were the strongest at that elevation. What we found could help solve the mystery of the damage increases. It seems the RFGFSs were falling below the elevation scan and crashing into the ground in the same region as the damage increase. This is leading us to believe that the RFGFSs themselves could be increasing the damage as they reach the ground and wrap around the circulation. This supports the findings of this paper because the tornado winds decreased during the majority of the surges so they are likely not responsible for the damage increase.

More support for this theory came when the spread of the damage was carefully analyzed. It seemed that there were some ‘bumps’ in the spread of the damage in some regions that lined up with the surge. If the surge was responsible for an increase in spread of damage, the increase should, to some extent, line up with the direction the surge was flowing. At 2008:41 UTC the first RFGFS is in full effect as it runs down the rear flank down draft. This time is also the strongest point of the surge, which can be seen on radar in correlation coefficient since the surges produce debris ejections. But in a
few short frames it disappears from correlation coefficient as it rushes towards the ground. At this time stamp, which is also the strongest point of the surge visually on radar, the surge was located just to the North of East of the tornado vortex. If you then reference appendix I, you can notice a bump in damage spread in the upper left hand side of the damage path just previous to the first RFGFS. The direction of the bump lines up very nicely with the direction the RFGFS originated from. What our thought is that as the RFGFS slammed into the ground as it wrapped around the parent circulation, it then caused the winds to increase in that region and spread the damage out further than the tornado vortex itself.

It seems a similar process occurs during surges 1, 2, 3, 4, 5, and 7. In an attempt to see if the ‘bumps’ lined up with the direction of the surge, we took the figure in appendix b and put arrows over each surge to signify the direction the surge was moving at our elevation. What we found seems to support that the RFGFS could have played a role in the damage done by the tornado during every surge except for the last. In appendix I, the same graph is shown as appendix B except for appendix I has the primary direction of the surge plotted over each surge. In surges 2 and 3 a bump of EF-1 damage just north of the primary path of the tornado can be seen. During the 4th surge a spread of EF-1 damage extends far south of the primary path. Similar to the past surges, correlation coefficient displays the surges being most intense in the same region as the bump in damage. After compiling all of this evidence, it is fair to theorize that the RFGFS did increase the intensity of the damage and the spread of it. The tornado slows during the majority of the surges yet the damage rating increases, suggesting the RFGFS could have helped increase the damage. When we display the primary direction of the surges over the damage map, a pattern of damage increase spread can be seen for surges 1, 2, 3, 4, 5, and 7. It could be argued that these increases come from unrelated sources such as satellite tornados or expansions in the tornado’s width, which is a possibility. But, since this study focused simply on this one case, drawing definitive conclusions is impossible. The data may not be perfect, but it does suggest that the surges that travel through a cyclic supercell’s down draft region can play a role on the intensity and spread of the damage caused by the tornado.