Analysis of MYRORSS Azimuthal Shear Observations of the Morning QLCS Mesovortices of 27 April 2011

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ABSTRACT

The most devastating day of the 2011 Super Outbreak, 27 April, started with a quasi-linear convective system (QLCS) forming in the early hours of the morning and tracking primarily through the southeastern United States producing multiple weak and strong tornadoes. Little research exists analyzing this first QLCS of the outbreak, and none has analyzed the azimuthal shear of the system during its non-tornadic and tornadic periods. This study aims to fill that research gap by using the Multi-Year Reanalysis of Remotely Sensed Storms (MYRORSS) database to collect 5-minute observations from the Weather Surveillance Radar 1988-Doppler (WSR-88D) network and align them with the radar-detected times of each mesovortex. In this project, the MYRORSS low-level and mid-level azimuthal shear products of the mesovortices embedded within the QLCS are compared to one another and the azimuthal shear values of the supercells. The average time difference between mesovortex initiation and tornadogenesis is also analyzed for all tornadoes produced by the QLCS, regardless of rating, and then compared between weak (EF0 and EF1) and strong tornadoes (EF2 and EF3). From this research, results show the low-level azimuthal shear values are mostly higher than or equal to the mid-level values and, when comparing the supercell azimuthal shear values to those of the QLCS, the supercells' values are higher overall. It was also discovered that the QLCS's average time between a mesovortex's initiation to the formation of its first tornado was found to be about 11.7 minutes, which is less than the mean lead time for all tornadoes warned in advance.

1. Introduction

27 April 2011 featured the most tornadoes within a 24-hour period on record in the United States (NOAA 2011; Knupp et al. 2014). It was the most destructive day of the 2011 Super Outbreak, which spanned from 26 April to 28 April with a total of 300 tornadoes produced (Knupp et al. 2014; Chasteen and Koch 2022a; Lyza et al. 2022). These storms were initiated with an amplified upper-level trough passage through the Southeast United States, succeeded by three shortwave troughs and strong jet streaks (Chasteen and Koch 2022a,b). As observed by Knupp et al. (2014), this day's storms were organized across three different episodes: an early morning quasi-linear convective system (QLCS), a midday QLCS, and the afternoon/evening discrete supercell storms. The focus of this paper will be on the morning QLCS and 47 of its tornadic mesovortices (Fig.1), excluding the large mesoscale vortex that formed over Northeastern Alabama due to the complex nature of the system.

A mesovortex is a small-scale, low-level rotational feature within a QLCS. QLCS mesovortices are generally sporadic due to the detrimental effects of the storms' cold pools, and associated QLCS tornadoes are also gener-

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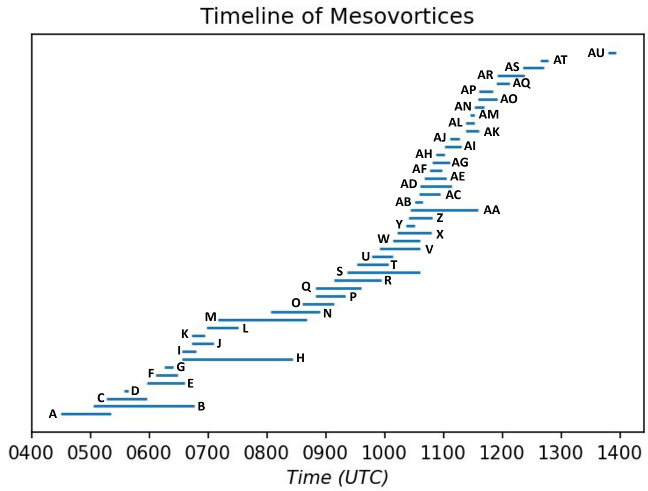

FIG. 1. Timeline of the 47 morning QLCS mesovortices from 27 April 2011 labeled alphabetically in order of formation.

ally weaker and short lived than their supercellular counterparts (Marion and Trapp 2021). The early morning QLCS formed around 2000 UTC on 26 April (Chasteen and Koch 2022a) as a series of supercells in the Arklatex area, and eventually produced numerous tornadoes across Louisiana, Mississippi, Alabama, Tennessee, Kentucky, Georgia, and Ohio. The first mesovortex developed about 0430 UTC (11:30 p.m. CDT on 26 April), followed by the first QLCS tornado around 0500 UTC (12 a.m. CDT on 27 April). Fifty-eight tornadoes are analyzed in this study.

This study uses the Multi-Year Reanalysis of Remotely Sensed Storms (MYRORSS; Williams et al. (2022a)) dataset to assess mesovortex evolution. MYRORSS utilizes the Weather Surveillance Radar 1988-Doppler (WSR-88D) network archived data in the Multi-Radar Multi-Sensor (MRMS) framework and from 1998–2011 to create a merged dataset with data in 5-minute increments (Williams et al. 2022b). A linear least squares derivative (LLSD) is applied to the WSR-88D data, which measures gradients of a scalar field where a least squares plane is adjusted to a local neighborhood of range bins (Mahalik et al. 2019). The LLSD method is effective in smoothing data to avoid poor data quality and overall make radar-derived measurements more noise tolerant (Smith and Elmore 2004; Miller et al. 2013; Newman et al. 2013). The MYRORSS database has 17 individual products including a variety of reflectivity types, echo tops with the associated heights, maximum expected size of hail, vertically integrated liquid, severe hail index, and azimuthal shear (Williams et al. 2022b). From the MYRORSS data, the maximum azimuthal shear values for both low-level (0–3 km) and mid-level (3–6 km) observations are analyzed in this study (Williams et al. 2022b).

Azimuthal shear is the result of using the LLSD method on gate-to-gate radial velocity. It is "measured in this case as the velocity difference (ΔV) divided by the distance between the two pixels in which the shear was observed" (Gibbs 2016). Previous studies have found that azimuthal shear values are often higher than ± 0.01 s^{-1} within strong circulations, like weak/typical-strength mesocyclones and mesovortices, and higher than ± 0.05 s^{-1} within the most extreme circulations, like very strong and/or tornadic mesocyclones or mesovortices (Mahalik et al. 2019). Azimuthal shear measurements are important to analyze for mesovortex and tornadogenesis research. Such research relating azimuthal shear to tornadogenesis within mesovortices has found that azimuthal shear values can be used to help determine if a mesovortex will become tornadic (Grana 2014) by analyzing how the values dramatically strengthen directly before tornadogenesis due to increasing strength and size of the mesovortex Atkins et al. (2005).

At the beginning stages of this research, it was hypothesized that the values for low-level azimuthal shear would overall mostly be higher than or equal to the midlevel azimuthal shear whenever a tornado was occurring. This was assumed because a previous study done by Grana (2014) showed that mesovortices form within the lowest 2.5 km of the atmosphere and build upwards. Another hypothesis was that the azimuthal shear values would be higher for the supercell mesocyclones than for the QLCS mesovortices. This reasoning was because radar velocity couplets through the WSR-88D network showed that rotational velocity is weaker and velocity couplets larger for QLCS tornadoes than supercell tornadoes overall (Thompson 2023), and QLCSs tend to produce weaker EF-0 and EF-1 tornadoes rather than strong EF-2 and EF-3 tornadoes associated more with supercells (Trapp et al. 2005; Smith et al. 2012; Marion and Trapp 2021). Comparing QLCSs to supercells has also proved that QLCSs usually have lower LCLs (Thompson et al. 2012) and account for less than half of the tornadoes recorded (Smith et al. 2012).

Possible reasons for QLCS tornadogenesis, such as the shearing instability dominant (SID) process that relies on a release of horizontal shear, or the pre-tornadic mesocyclone dominant (PMD) process, and the seasons when each mostly dominates (Goodnight et al. 2022) have been analyzed. Studies that have compared azimuthal shear between non-tornadic and tornadic mesovortices found that mesovortices that were tornadic usually lasted longer and were deeper and stronger than non-tornadic mesovortices and were known to intensify and deepen even more right before tornadogenesis occurred (Atkins et al. 2004, 2005). The greatest differences between tornadic and non-tornadic mesovortices lie within the lowest 2.5 km of the atmosphere (Atkins et al. 2004; Grana 2014).

Looking more specifically at the morning QLCS of the 27 April 2011 outbreak, there have been studies of how the early morning QLCS impacted the environment for the rest of the outbreak and amplified the conditions for the supercells to form by creating an increase in vertical wind shear, an intensification in the low-level jet, and a significant thermal boundary (Knupp et al. 2014; Chasteen and Koch 2022a,b; Lyza et al. 2022). Chasteen and Koch (2022b), suggested that the morning QLCS may have substantially altered its own near-inflow environment, contributing to additional strengthening of the system and more prolific mesovortex production. Despite all of these studies, however, there has not been an in-depth study examining azimuthal shear values for the morning QLCS of 27 April 2011, which was quite an anomaly with its multiple strong tornadoes. The research and results explained in this paper help fill this gap and expand our knowledge about QLCS mesovortices and tornadoes. It is possible that this research and similar studies could ultimately help better predict and warn against QLCS tornadoes. As stated by Lyza et al. (2022), there could be, though limited, a capability for anticipating tornadogenesis within a storm within 30 minutes through observing trends in azimuthal shear in similar situations. More specific goals of this paper are to observe the time gaps between mesovortex formation and tornadogenesis, analyze the maximum low-level and midlevel azimuthal shear values for each of the 47 mesovortices, compare these values to the maximum azimuthal shear values for the supercell mesovortices (Lyza et al. 2022), and compare maximum azimuthal shear values between weak and strong tornadoes for both the QLCS only and in comparison to the supercell tornadoes once more. The remainder of this paper will discuss the data and methods used in section 2, results found in section 3, a discussion about the previously stated results following in section 4, and the summary and conclusions of this research in section 5.

2. Data and methods

a. Data collection

The initial dataset for this research consisted of radar-gathered information on each of the 47 individual mesovortices within the QLCS, using information from the closest individual WSR-88D radar to the mesovortex. The data listed the associated UTC time, radar used, elevation, maximum inbound (v_{in}) and outbound (v_{out}) radial velocities, latitude and longitude of vin and vout, azimuths, heights, and ranges for each v_{in} and v_{out} value, mesovortex latitude and longitude, mesovortex location within the QLCS relative to the axis of the primary convective line (ahead of, embedded within, or trailing behind), and the tornado flag (if there was a tornado at the stated time and if so, its rating) for each mesovortex. Taking this data, the corresponding times of the MYRORSS merged azimuthal shear observations were applied for both the low (0–3 km) and mid (3–6 km) levels of the mesovortices. Since the MYRORSS observation times did not perfectly align with the radar observation times in the spreadsheet, starting times used were from either at the exact mesovortex initiation time, if applicable, or the closest observation after initiation (since the timestamp on each MYRORSS file represents the end of a 5-min data merging period). Ending times were also used from either exactly at the mesovortex conclusion or afterward. Another issue arose while aligning MYRORSS observation times to the mesovortex radar times where there were multiple mesovortex radar times for one 5-minute MYRORSS observation. To resolve this complication, the time with the largest rotational velocity (V_{ROT}) value was kept due to the direct relationship between V_{ROT} and azimuthal shear. V_{ROT} is the value resulting from taking half of the difference between the mesovortex inbound (v_{in}) and outbound (v_{out}) velocity (Atkins et al. 2005). Applying the MYRORSS observations with the time range for each mesovortex resulted in a table containing maximum azimuthal shear with the associated mean latitude, mean longitude and tornado flag.

b. Methods for finding statistical significance and median values, and mapping mesovortices' paths

Once maximum azimuthal shear was computed for all 47 mesovortices, the maximum value of low-level and midlevel azimuthal shear during each tornado's life span was then collected and organized with corresponding times and tornado ratings. If two or more tornadoes within the same mesovortex occurred simultaneously, only the tornado with the highest azimuthal shear value was kept for

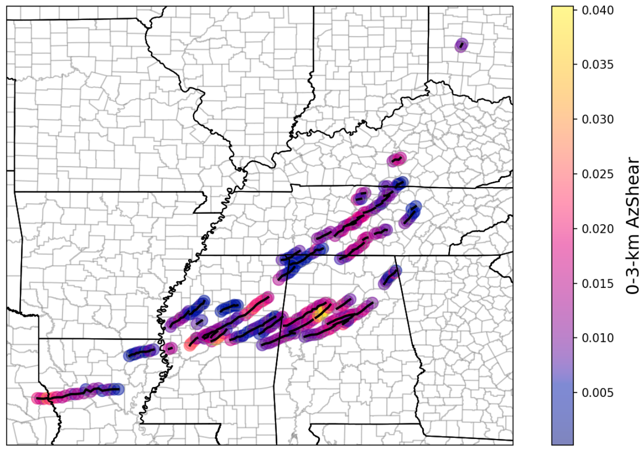

FIG. 2. QLCS mesovortex tracks plotted using mean latitude and longitude with associated low-level (0–3 km) azimuthal shear observations at each point.

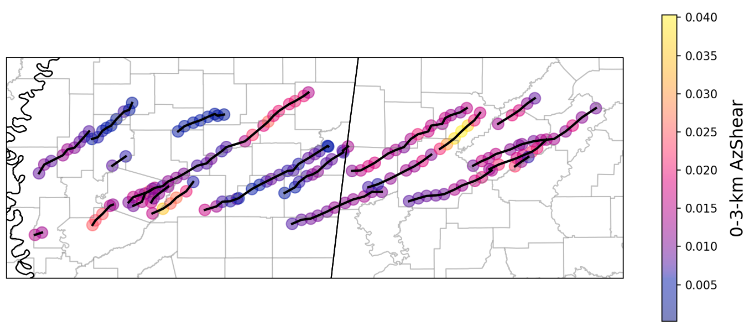

FIG. 3. Close-up of morning QLCS mesovortex tracks group in Mississippi and Alabama plotted using mean latitude and longitude with associated low-level (0–3 km) azimuthal shear observations at each point.

that time range. For example, tornadoes H3 and H4 overlapped one another, and as a result, only H4 was kept in the study because it was stronger. The same method was also used for the outbreak's supercell study (Lyza et al. 2022). The maximum azimuthal shear data were then analyzed to make statistical comparisons. Starting by addressing the first hypothesis, we compared the maximum values of low- and mid-level azimuthal shear during each tornado. The purpose of this comparison was to analyze the relation between low-level and mid-level values. Two Welch's t-tests were also conducted to find the p-value when differentiating the low-level azimuthal shear values of weak tornadoes (EF0 and EF1) to strong tornadoes (EF2 and EF3) and the midlevel azimuthal shear of weak tornadoes to strong tornadoes. Assuming that the variances between all datasets were unequal, Welch's t-tests were necessary for determining if there was a statistically significant difference between the weak-rated and strong-rated tornadoes when analyzing the azimuthal shear. Violin plots were also made to visualize the comparison of the median of azimuthal shear values between weak and strong tornadoes at each level.

Another analysis was done viewing the time difference between mesovortex initiation and the first tornado displayed through a violin plot. The difference in time was then also analyzed between weak and strong tornadoes with a violin plot and a Welch's t-test. All tornado start times were rounded to the nearest minute for this study with some needing to be estimated due to inaccurate past documentation of times for the event. Furthermore, all 47 mesovortices' paths were also mapped out using the associated mean latitudes and longitudes with the maximum low-level azimuthal shear plotted along each point of the paths (Fig.2, Fig.3).

c. Methods for comparing longest lived and EF3-producing mesovortices

Another way the QLCS mesovortices were analyzed in comparison to one another was by plotting the maximum azimuthal shear values of the top 3 longest-lived mesovortices together. The three mesovortices with the longest durations in order from longest to shortest were mesovortex H, mesovortex B, and mesovortex M, respectively. Further comparison consisted of plotting the azimuthal shear values from all mesovortices that produced at least one EF3 tornado together. The mesovortices that produced EF3 rated tornadoes are mesovortex H (which produced two EF3s), mesovortex T, mesovortex V, and mesovortex W. The times of tornadogenesis for each mesovortex are plotted alongside the data as well to display the changes in azimuthal shear before, during, and after the tornadoes.

d. Method for comparing QLCS and supercell observations

Next, the QLCS's maximum azimuthal shear values were compared to the values of the supercells from the outbreak. Ignoring the supercell tornadoes categorized as violent (EF4 and EF5), violin plots were created visually showing differences in the median of azimuthal shear between weak QLCS and supercell tornadoes and strong QLCS and supercell tornadoes. The data were once again analyzed at both the lower and mid-levels. To determine the significance of the differences in the datasets, more Welch's t-tests were conducted. For these tests, the low-level azimuthal shear between weak QLCS tornadoes was set against the weak supercell tornadoes, the low-level azimuthal shear between strong QLCS tornadoes was set against the strong supercell tornadoes, the mid-level azimuthal shear between weak QLCS tornadoes was set against the weak supercell tornadoes, and the mid-level azimuthal shear between strong QLCS tornadoes was set against the strong supercell tornadoes.

3. Results

a. Comparing mesovortex values

In the methods of this project, the highest value of azimuthal shear observed during a tornado was identified in each mesovortex for examination. Out of the 58 tornadoes, 46 resulted with the highest maximum value being collected within the low-level observations. The remaining 12 tornadoes are split up into 10 resulting in the highest value being equal in both the low- and mid-level observations (tornadoes B1, B2, B4, C1, E1, P2, Q1, R1, AS1, and AT1) and two resulting with the highest value coming from the mid-level observations (tornadoes A1 and AQ1). Note that all times listed in this paper are rounded to the nearest minute. The highest observed azimuthal shear value recorded during a tornado occurred around 1025 UTC (5:25 a.m. CDT) in mesovortex W (Fig.4). This value was recorded at .04033 s^{-1} in the low-level observations of the mesovortex. The highest observed value recorded during a non-tornadic period occurred around 1020 UTC (5:20 a.m. CDT) also in mesovortex W. This value was recorded at 0.03814 s^{-1} in the low-level observations of the mesovortex. The lowest observed azimuthal shear value recorded during a tornado occurred around 1212 UTC (7:12 a.m. CDT) in mesovortex AQ. This value was recorded at 0.00086 s^{-1} in the low-level observations of the mesovortex. The lowest observed value during a non-tornadic period was recorded around 1206 UTC (7:06 a.m. CDT) in mesovortex AR. This value was recorded at 0.00021 s^{-1} in the low-level observations of the mesovortex. It was noted that the mesovortices, once detected by radar, began with either an increase or decrease in azimuthal shear.

Focusing solely on the three longest mesovortices (B, H, and M) (Fig.5), mesovortex B (Fig.6) is examined to have the highest peak in azimuthal shear for both the low-level and mid-level observations. The highest value was 0.02877 s^{-1} in the low-level observations and 0.02877 s^{-1} in the mid-level observations. Mesovortex H (Fig.7) follows as having the second highest peak in values of 0.02622 s^{-1} in the low-level observations and 0.01404 s^{-1} in the mid-level observations. Studying the four EF3-producing mesovortices from the QLCS (Fig.8), azimuthal shear peaks are observed to occur around tornadogenesis, either immediately following or shortly thereafter. All low-level azimuthal shear values from these mesovortices are within the 0.00634–0.04033 s^{-1} range and all mid-level values are within the 0.0019 - 0.01404 s^{-1} range. Timewise, there was a large gap after mesovortex H in which no EF3 tornadoes were produced, and after the demise of mesovortices V and W around nearly 1100 UTC (6 a.m. CDT), there were no further EF3 tornadoes for the remainder of the event.

b. Statistical significance

Different Welch's t-tests were completed to determine which data comparisons are significant statistically. The t-test performed between low-level weak and strong tornadoes in the QLCS resulted in a p-value of 0.0002. The test

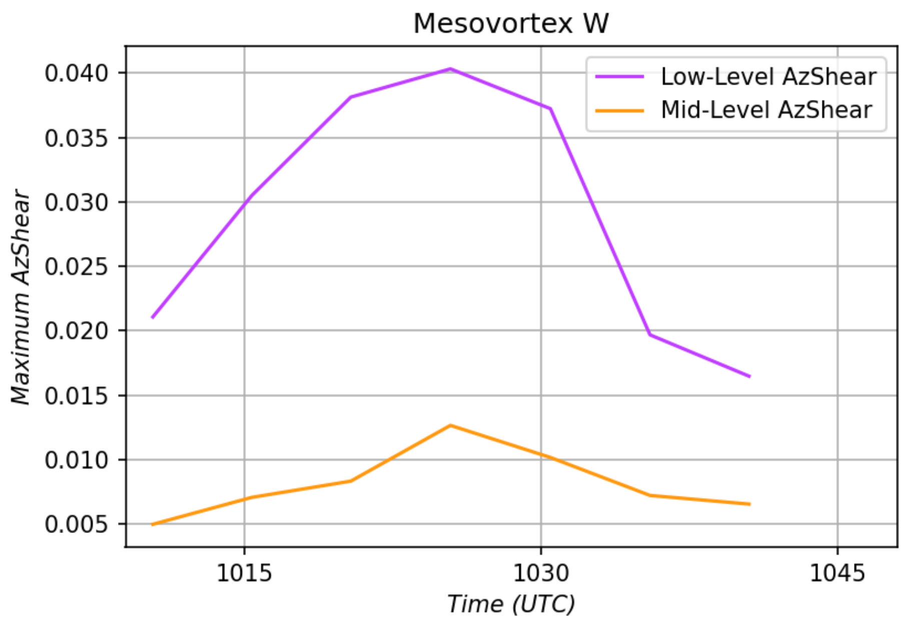

FIG. 4. Comparison of low-level (0–3 km) and mid-level (3–6 km) azimuthal shear observations in Mesovortex W (Contained the highest value of azimuthal shear of the QLCS and produced an EF3 tornado).

between mid-level weak and strong tornadoes in the QLCS resulted in a p-value of 0.000001. Between weak tornadoes' low-level values in the supercells and QLCS, the p-value was 0.000004. For the significance between strong tornadoes' low-level values in the supercells and QLCS, a p-value of 0.02 resulted from the test. The Welch's t-test between weak tornadoes' mid-level values in the supercells and QLCS resulted in a p-value so small this study rounds the value to 0. Finally, between strong tornadoes' mid-level values in the supercells and QLCS, the p-value was 0.0002. The p-value results from these data convey that the relationships between all of the previously-listed datasets are statistically significant with 99% confidence. The data's significance is further discussed in the following section.

c. *Weak vs. strong tornadoes*

With the highest azimuthal shear values collected during a tornado for each mesovortex, this study analyzed 37 weak tornadoes and 21 strong tornadoes from the QLCS. When comparing the low-level azimuthal shear observations between weak (EF0 and EF1) and strong (EF2 and EF3) tornadoes (Fig.9), the maximum, minimum, and median values are all higher for stronger tornadoes. The same was found to be true for mid-level observations, only the differences are less significant in comparison. For the low-level observations, the median value was 0.00991 s^{-1} for weak tornadoes and 0.01843 s^{-1} for strong tornadoes. The maximum was 0.02478 s^{-1} for weak tornadoes and 0.04033 s^{-1} for strong tornadoes, and the minimum was 0.00425 s^{-1} for weak tornadoes and 0.01029 s^{-1} for strong tornadoes. For the mid-level observations, the median value was 0.00574 s^{-1} for weak tornadoes and 0.01202 s^{-1} for strong tornadoes. The maximum was 0.01311 s^{-1} for weak tornadoes and 0.02329 s^{-1} for strong tornadoes, and the minimum was 0.00234 s^{-1} for weak tornadoes and 0.00685 s^{-1} for strong tornadoes.

d. *QLCS vs. supercell tornado observations*

To compare the azimuthal shear observations from the QLCS to those of the supercell outbreak on 27 April (Fig.10), 48 weak tornadoes and 27 strong tornadoes from the supercells were analyzed using the dataset from Lyza et al. (2022). For the low-level supercell observations, the median value was 0.016 s^{-1} for weak tornadoes and 0.02321 s^{-1} for strong tornadoes. The maximum was 0.02741 s^{-1} for weak tornadoes and 0.04677 s^{-1} for strong tornadoes. The minimum was 0.00591 s^{-1} for weak tornadoes and 0.00719 s^{-1} for strong tornadoes. For the mid-level supercell observations, the median value was 0.01439 s^{-1} for weak tornadoes and 0.01704 s^{-1} for strong tornadoes. The maximum was 0.02297 s^{-1} for weak tornadoes and 0.04003 s^{-1} for strong tornadoes. The minimum was 0.0048 s^{-1} for weak tornadoes and 0.00903 s^{-1} for strong tornadoes. When comparing the azimuthal shear observations between weak and strong tornadoes in the QLCS and supercells, the maximum and median values are all higher for the supercell observations. In all cases, the strong tornado observations had the highest median values. There is a greater gap in the medians between

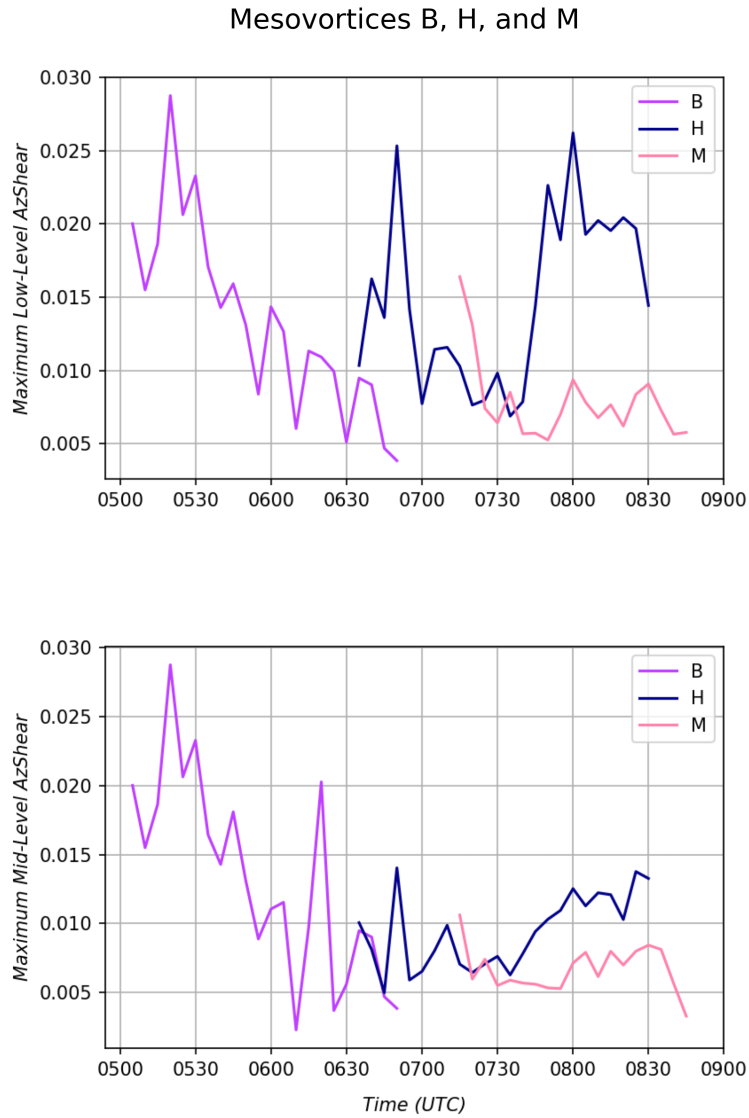

FIG. 5. Comparison of low-level (0–3 km) azimuthal shear (top) and mid-level (3–6 km) azimuthal shear (bottom) observations in the top three longest-lived mesovortices (B, H, and M).

weak tornadoes when comparing the supercell values to those of the QLCS in each distinct level, and there is a greater gap in the maximums between strong tornadoes when comparing the supercell values to those of the QLCS in each distinct level. Except for the low-level strong tornado observations, all cases are also higher within the supercells for the minimum values. These results in comparison to values from the mesovortices are nearly all in agreement with the authors' hypothesis on the azimuthal shear relation between QLCSs and supercells as will be discussed in the next section.

e. Time between mesovortex initiation and tornadogenesis

To determine an average time until tornadogenesis in the QLCS, the time gap in minutes between each mesovortex's initiation and the formation of its first tornado was calculated. For the difference in time for all tornadoes between mesovortex initiation and tornadogenesis (Fig.11), the mean time was about 11.7 minutes, the median time was about 8 minutes, and the maximum was 63 minutes. Results from characterizing the time difference between weak and strong tornadoes as before (Fig.12) show the mean time to be about 9.7 minutes for weak tornadoes

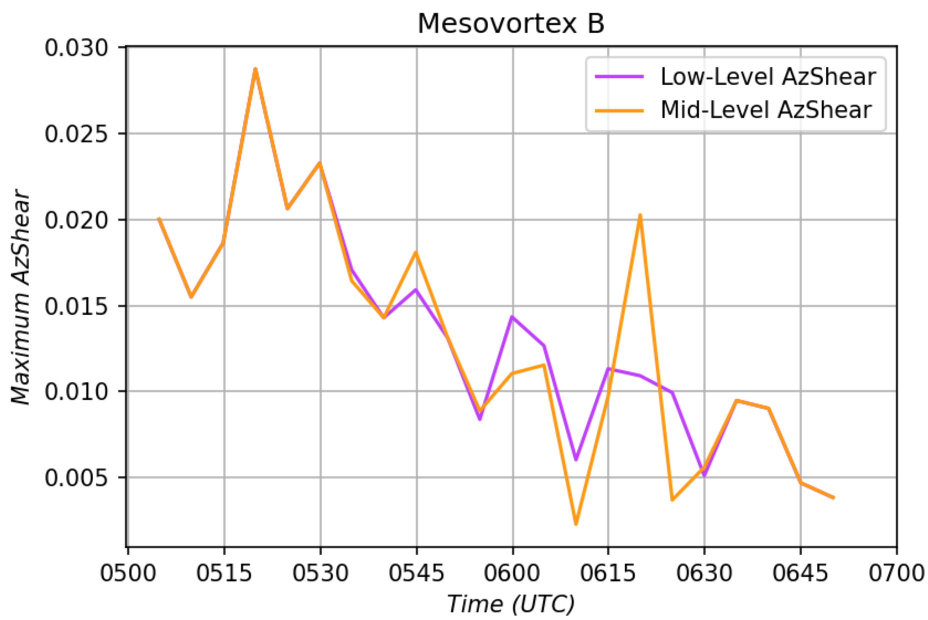

FIG. 6. Comparison of low-level (0–3 km) and mid-level (3–6 km) azimuthal shear observations in Mesovortex B (second longest-lived mesovortex with the most tornadoes).

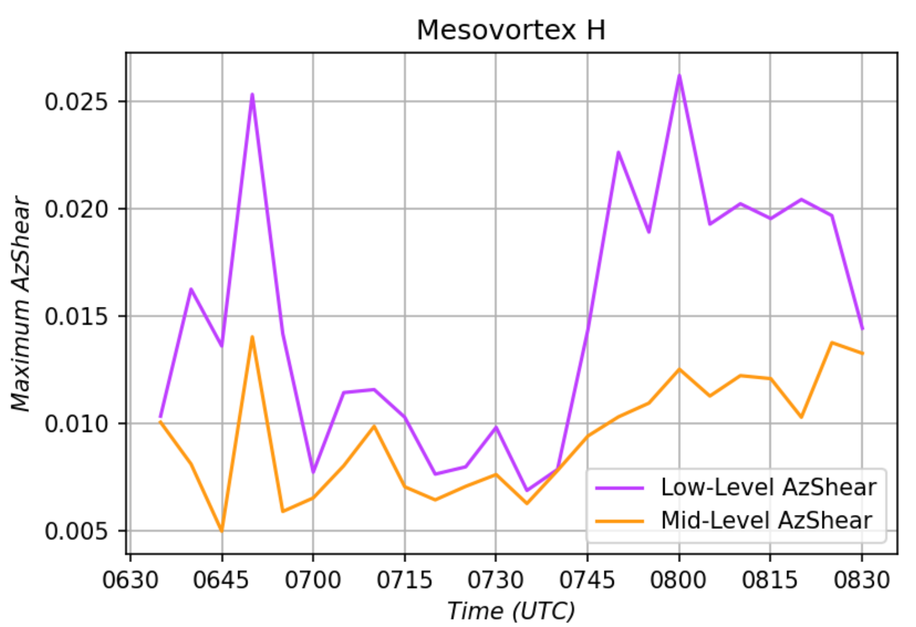

FIG. 7. Comparison of low-level (0–3 km) and mid-level (3–6 km) azimuthal shear observations in Mesovortex H (longest-lived mesovortex and produced two EF3 tornadoes).

and 15.1 minutes for strong tornadoes. The median time difference was found to be about 6 minutes for weak tornadoes and about 12.5 minutes for strong tornadoes. The maximum difference in times for weak tornadoes was 63 minutes for weak tornadoes and 49 minutes for strong tornadoes. The Welch's t-test between the weak and strong tornado lead times resulted in a p-value of 0.1429. As a result, the difference in the mean time from mesovortexgenesis and tornadogenesis for weak vs. strong tornadoes is not statistically significant (at least not at the 90% confidence level); however, the fact that this timeframe is nearly double for strong tornadoes vs. weak ones (over 12 mins

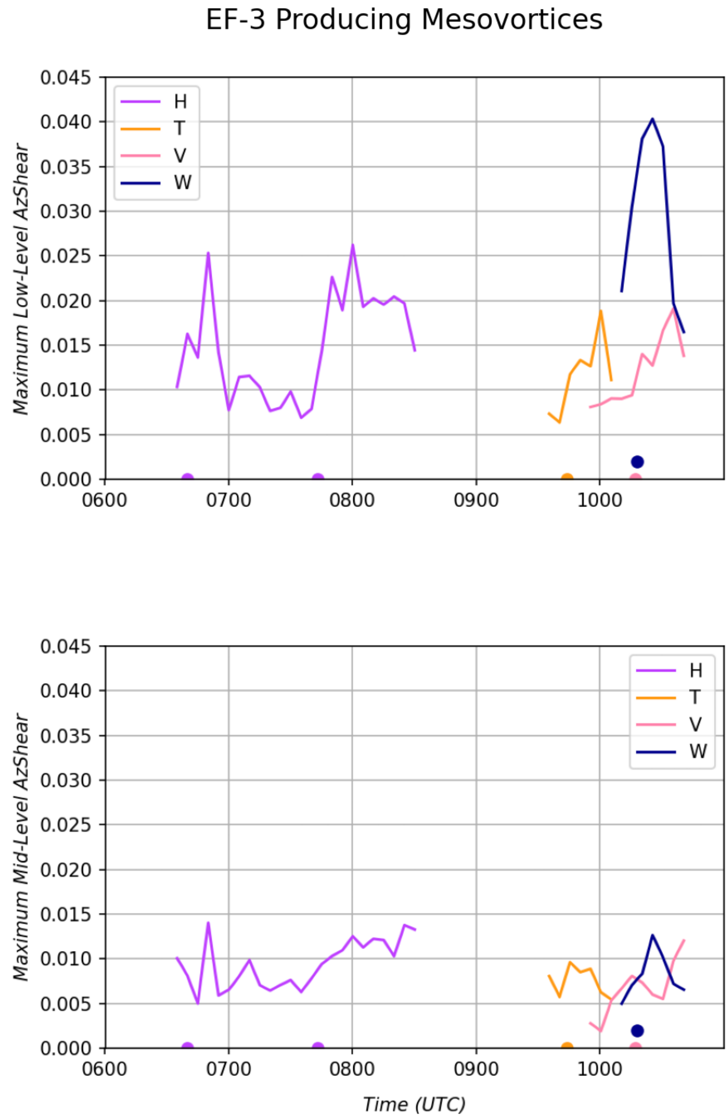

FIG. 8. Comparison of low-level (0–3 km) azimuthal shear (top) and mid-level (3–6 km) azimuthal shear (bottom) observations in the four mesovortices that produced EF-3 tornadoes (H, T, V, and W) with tornadogenesis times plotted along the bottom of the plot, color-coded to the associated mesovortex.

vs. 6 mins, respectively) suggests that while the difference is not statistically significant, it may be operationally useful. We discuss this further in the next section.

4. Discussion

a. Statistical significance

The results of the Welch's t-tests for both the low- and mid-level observations between weak and strong tornadoes from the QLCS, and the low- and mid-level observations of weak and strong tornadoes from the QLCS and supercells together show statistical significance. According to Welch (1947), p-values of 0.05 or lower indicate that there is a 95% confidence that the means of two different populations are different from one another. As can be seen in section 3a, every t-test resulted in a p-value less than 0.05, indicating that the differences in means are statistically significant with 95% confidence for all of the comparisons made. The most significant comparison in the QLCS alone was between the weak and strong mid-level observations with a p-value of 0.000001. The most significant comparison between the QLCS and supercells was the mid-level weak observations with a p-value of 0. The Welch's t-tests conducted conclude that the azimuthal shear values for the weak and strong tornadoes of the QLCS are significantly different from each other in the 27 April 2011 morning QLCS.

b. Mesovortex azimuthal shear values

Consistent with the study's initial hypothesis on the maximum low-level azimuthal shear observations during a tornado being mostly higher than or equal to the mid-level observations, results show that this was indeed the case for all but 2 of the 58 tornadoes. The tornadoes with higher reported mid-level values of azimuthal shear are thought to be a result of the study not accounting and correcting for mesovortex distance from the associated radar. These two tornadoes were an exceptional distance away (both horizontally and vertically) from the radars that detected them, and therefore, the radars were not able to get an accurate reading on the lowest 0–3 km of the systems. The low-level observations of tornadic mesovortices being mostly stronger than the mid-level observations are in agreement with results found in Atkins et al. (2005). The range of azimuthal shear values within the QLCS fit within the range stated by Mahalik et al. (2019) ranging from ±0.01 s^{-1} to ±0.05 s^{-1} with the highest value peaking at 0.04033 s^{-1} in mesovortex W during an EF3 tornado and the lowest value being 0.00021 s^{-1} in mesovortex AR during a non-tornadic period. The lowest azimuthal shear value recorded during a tornado was 0.00086 s^{-1} within the 0–3 km layer. Results show that when comparing the low-level observations to the mid-level observations, the low-level median values are higher than the mid-level values by 0.00417 s^{-1} for weak tornadoes and 0.00641 s^{-1} for strong tornadoes. For maximum values, the low-level values are higher than the mid-level values by 0.01167 s^{-1} for weak tornadoes and 0.01704 s^{-1} for strong tornadoes. For the minimum values, the low-level values are higher than the mid-level values by 0.00191 s^{-1} for weak tornadoes and 0.00344 s^{-1} for strong tornadoes. The greatest difference in azimuthal shear between the low-level and mid-level observations was found to be for the maximum values of strong tornadoes. Comparing weak tornadoes to strong tornadoes, median azimuthal shear values are higher for strong tornadoes by 0.00852 s^{-1} in the low-level observations and by 0.00628 s^{-1} in the mid-level observations. This finding is consistent with results from both Dowell et al. (2005) and Smith et al. (2015), disregarding the tornado's range from radar, showing that stronger tornadoes are associated with higher velocity signatures. This study also analyzed the azimuthal shear values leading up to tornadogenesis to see if any patterns could be found. Unlike the suggestion of low-level azimuthal shear strengthening dramatically prior to tornadogenesis proposed by Atkins et al. (2005), there is no distinct pattern in azimuthal shear values leading up to tornado formation. Azimuthal shear was seen to both increase and decrease before tornadogenesis, and dramatic increases in azimuthal shear beforehand are not seen consistently enough to make a definite conclusion.

c. QLCS vs. supercell azimuthal shear values

The study's second hypothesis also proved to be consistent with the results found from comparing the outbreak's supercell azimuthal shear values to those of the QLCS. In comparison, there are 11 more weak and six more strong tornadoes from the supercells than there are from the QLCS. It was hypothesized that the values would be higher for the mesocyclones than for the mesovortices, and this was the case for all but the minimum values during strong tornadoes within the low-level observations. The low-level median values are higher by 0.00609 s^{-1} for weak tornadoes and 0.00478 s^{-1} for strong tornadoes from the mesocyclones. For mid-level observations, the median values are higher by 0.00865 s^{-1} for weak tornadoes and 0.00502 s^{-1} for strong tornadoes from the mesocyclones. The low-level maximum values are higher by 0.00263 s^{-1} for weak tornadoes and 0.00644 s^{-1} for strong tornadoes from the mesocyclones. For mid-level observations, the maximum values are higher by 0.00986 s^{-1} for weak tornadoes and 0.01674 s^{-1} for strong tornadoes from the mesocyclones. For the minimum values, the low-level weak tornado observations and both of the mid-level observations stayed consistent as well with the mesocyclone values being higher by 0.00166 s^{-1} for low-level weak tornadoes, 0.00246 s^{-1} for mid-level weak tornadoes, and 0.00218 s^{-1} for mid-level strong tornadoes. The low-level value for the mesocyclones' strong tornadoes, however, was inconsistent with the hypothesis with the values being less than the QLCS's value by 0.0031 s^{-1}.

The overall findings in this study between the mesocyclones' and QLCS's azimuthal shear are consistent with similar findings in Thompson (2023) stating that a weaker V_{ROT} (given the close relation between V_{ROT} and azimuthal shear) is usually associated with QLCS tornadoes when compared to supercell tornadoes. The greatest difference in azimuthal shear between the mesocyclones and mesovortices took place for the mid-level strong tornado maxima observations. Overall, the differences in azimuthal shear between the mesocyclones and QLCS are greatest for the mid-level observations for all categories except the minimum values between strong tornadoes. Given that mesovortices are mainly lower-level features, this conclusion can be considered a reasonable one.

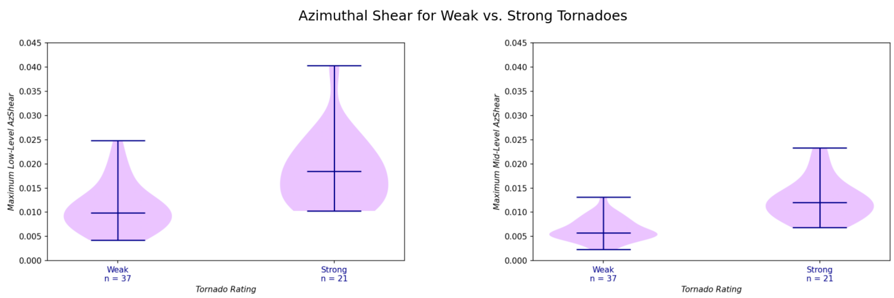

FIG. 9. Comparison of maximum low-level (0–3 km) azimuthal shear (left) and mid-level (3–6 km) azimuthal shear (right) observations between weak (EF0 and EF1) and strong (EF2 and EF3) tornadoes from the morning QLCS.

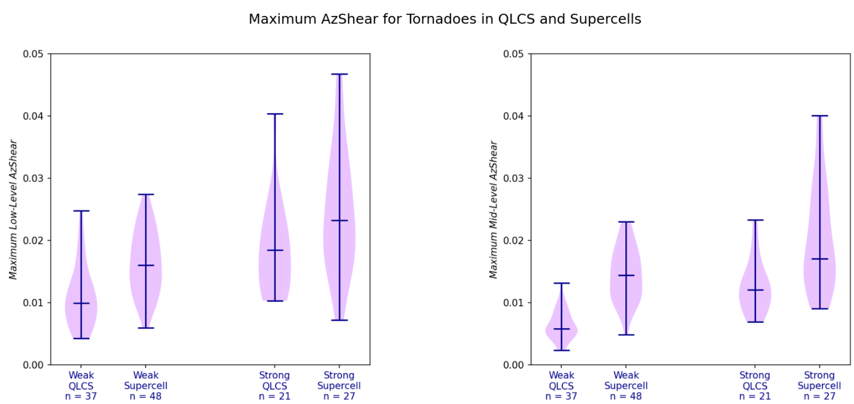

FIG. 10. Comparison of maximum low-level (0–3 km) azimuthal shear (left) and mid-level (3–6 km) azimuthal shear (right) observations between weak (EF0 and EF1) and strong (EF2 and EF3) tornadoes from the 27 April 2011 morning QLCS and supercells.

d. Three longest-lived mesovortices and EF3-producing mesovortices

After analyzing the three longest-lived mesovortices (B, H, and M), results showed the highest value of the three to be observed in mesovortex B at 0.02877 s^{-1} in both the 0–3 km and 3–6 km layers. These values did not take place during a tornado but rather were recorded close to 10 minutes before the mesovortex's first tornado (B1), which was rated an EF2. The second-highest values for both levels, observed in mesovortex H, were different from one another and both occurred during a tornado. The second-highest low-level value was recorded at 0.02622 s^{-1} during EF3 tornado H4. The second-highest mid-level value was recorded during EF3 tornado H1 at 0.01404 s^{-1}. It can be concluded from these findings that strongly-rated tornadoes are not always associated with the highest azimuthal shear values in a QLCS as a higher value was observed during a pre-tornadic period for an EF2 rather than during the lifetime of an EF3, despite strong tornado ratings being associated with high values in general.

The analysis of the four mesovortices that produced EF3 tornadoes displayed values as low as 0.0019 s^{-1} and as high as 0.04033 s^{-1}. As expected, the lowest value was recorded in the mid-level observations, and the highest value was recorded in the low-level observations. As can be seen in Fig.8, peaks in azimuthal shear happened either immediately after or shortly following tornadogenesis. This pattern was also viewed in all 47 mesovortices. A similar pattern was also observed by Lyza et al. (2019) for the Kankakee Valley mesovortices. Following the last EF3 tornadoes in mesovortices V and W, the QLCS seemed to begin deteriorating in strength and intensity. This deterioration is indicated by all mesovortices succeeding V and

W, except for mesovortex AA, lasting fewer than 35 minutes individually and producing mostly all weak tornadoes with the exception of a few EF2s.

e. Average time differences between mesovortex initiation and tornadogenesis

Looking at the time it took for a mesovortex's first tornado to form, the results of this study show the mean difference in time between mesovortex initiation and tornadogenesis to be about 11.7 minutes with a median time difference of 8 minutes, regardless of tornado rating. On average, stronger tornadoes take longer to form from mesovortex-genesis than weaker tornadoes, with weak tornadoes averaging at about 9.7 minutes compared to 15.1 minutes for strong tornadoes and weak tornadoes having a median time difference of about 6 minutes compared to 12.5 minutes for strong tornadoes. Despite strong tornadoes requiring more time to form in mesovortices overall, the maximum time difference occurred for the weak, EF1 tornado U at about 63 minutes. For strong tornadoes of the QLCS, the longest time for tornadogenesis took place for EF2 tornado AA at about 49 minutes. Findings in Atkins et al. (2005) are in agreement with the average time between mesovortex-genesis and tornadogenesis being about 12 minutes in general. However, Atkins et al. (2005) only analyzed weak-rated tornadoes within a bow echo, and there were also only 5 tornadoes in total. When comparing the findings from that study to the difference in time for weak tornadoes in this study, there is around a 2-minute difference. The minimum time difference was negative in this study because a few of the tornadoes formed before the associated mesovortices were detected by radar. The p-value between the weak and strong tornado start times was greater than 0.05 (0.1429), indicating only around 85% confidence that the means of the two populations are different from one another. Although this difference is not statistically significant, it is striking that the median time between mesovortex-genesis and strong tornadogenesis is double the median time between mesovortex-genesis and weak tornadogenesis. Also, both of these median times (12.5 and 6 mins respectively) are less than the mean lead time for tornadoes warned in advance, which is around 15 mins (at least in the early 2010s; Brooks and Correia (2018)). This suggests that a tornado warning issued on a soon-to-be tornadic mesovortex, once that mesovortex has already formed, will likely yield a lead time less than the national average. Thus, improving lead time of QLCS mesovortex tornadoes may be driven by a better understanding of processes leading to the initial genesis of tornadic mesovortices, not necessarily the processes resulting in tornadogenesis once a mesovortex has formed.

5. Summary and conclusions

The purpose of this paper was to analyze the low-level and midlevel maximum azimuthal shear values, analyze those observations during tornadic periods, compare the azimuthal shear observations between the mesocyclones and mesovortices of the 27 April outbreak, and observe the time between mesovortex-genesis and tornadogenesis. To do so, azimuthal shear observations were collected through the MYRORSS database and were aligned with the radar-detected mesovortex times in 5-minute increments. The maximum azimuthal shear values recorded during tornadoes were then collected and analyzed. This study helps fill the gap existing in research on the 27 April outbreak's morning QLCS and helps to grow the current knowledge about QLCS mesovortices as a whole. The findings in this paper that help add to the knowledge of QLCSs and mesovortices could eventually aid in future forecasting developments.

The findings of this research the authors consider to be the most important are as follows:

- Within the QLCS mesovortices, low-level observations were higher than mid-level observations in general during both weak and strong tornadoes. Results show that azimuthal shear is higher for the median, maximum, and minimum values.

- On average, strong tornadoes are associated with higher azimuthal shear values than weak tornadoes, although this is not universally the case.

- The greatest difference in low-level and mid-level azimuthal shear recorded is between the maximum values in strong tornadoes.

- The highest azimuthal shear value recorded in the QLCS was observed in mesovortex W at 0.04033 s^{-1}. This value occurred during the mesovortex's EF3 tornado.

- Within the mesovortices, there are noticeable peaks in azimuthal shear immediately after tornadogenesis, similar to findings in Lyza et al. (2019).

- After comparing the 27 April supercell's azimuthal shear observations to those of the QLCS, the mesocyclones have higher values than the mesovortices overall. For all but the low-level observations during strong tornadoes, the median, maximum, and minimum values were higher for the mesocyclones' azimuthal shear.

- The greatest difference in azimuthal shear recorded between the mesocyclones and mesovortices values is mostly in the mid-level observations. The difference in minimum values during strong tornadoes

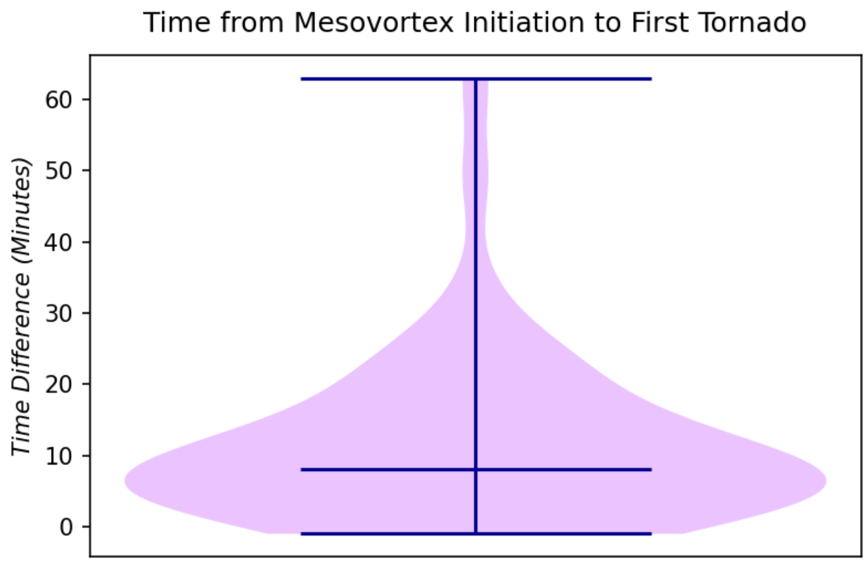

FIG. 11. Median time difference (minutes) between mesovortex initiation and formation of a mesovortex's first tornado.

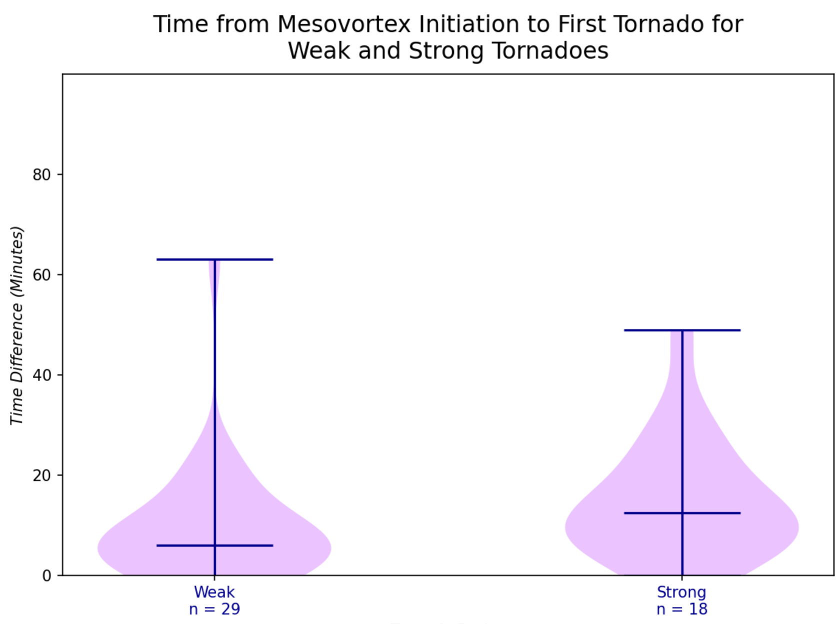

FIG. 12. Comparison of the median time difference (minutes) between mesovortex initiation and the formation of a mesovortex's first tornado analyzed for weak (EF0 and EF1) and strong (EF2 and EF3) tornadoes from the morning QLCS.

compared between the mesocyclones and mesovortices was greater in the low-level observations instead.

- The average time it took for the first tornado to form after mesovortex genesis for all tornadoes, regardless of rating, was about 11.7 minutes. The median difference in time was about 8 minutes.

- The average time it took between mesovortex genesis and tornadogenesis for weak tornadoes was about 9.7 minutes, and the median difference in time was about 6 minutes. The average time it took between mesovortex genesis and tornadogenesis for strong tornadoes was about 15.1 minutes, and the median difference in time was about 12.5 minutes.

In conclusion, this was a limited and novel study of the morning QLCS on 27 April 2011 and the associated azimuthal shear values. There are many opportunities expand upon these findings. Future studies should be done to bring about more clarity of and knowledge for these storms and to correct for limitations and estimations of this particular study. For example, a few of the tornadoes' start times had to be estimated due to inaccurate records of the outbreak's tornadoes, making it where tornadogenesis occurred before radar-detection of the mesovortex and should be corrected if accurate information is made available. Comparison between tornado lead times for weak and strong tornadoes is substantial enough to provoke further study with a larger data set of multiple cases. This study also used azimuthal shear values derived using the LLSD method, which, according to Mitchell and Elmore (1998), Miller et al. (2013), and Newman et al. (2013), may possibly underestimate values. With the limited amount of time given for this research project, this study was unable to include information about a mesovortex's distance from the nearest WSR-88D radar. This information is important to analyzing azimuthal shear values and should be accounted for in future studies of this QLCS and its tornadoes.

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Data availability statement. Access to the MYRORSS dataset is given through (doi.org/10.15763/DBS.CIMMS.MYRORSS.DATA). The WSR-88D radar data can be downloaded via NCEI (https://www.ncdc.noaa.gov/nexradinv/). The SPC ONETOR database can be accessed and downloaded at (https://www.spc.noaa.gov/wcm/).

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