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Article

Tornado Radar Images and Path Directions

An Assessment of Public Knowledge in the Southeastern United States

Jason C. Senkbeil, Kathleen Sherman-Morris, Walker Skeeter, and Cole Vaughn

ABSTRACT: Due to the current use and reliance on tornado warning polygons, several published articles have concentrated on themes related to risk perception and interpretation of risk within and outside of polygons. Despite the general success of warning polygons, not everybody is able to spatially estimate their risk by looking at maps with tornado warning polygons. Using polygons in conjunction with radar images can improve comprehension and better inform protective action decision-making for tornado warnings. Additionally, a potential latent area of research is how past tornado tracks and climatological knowledge about tornado path directions may influence tornado risk perception and protective action decision-making. In this study, we surveyed 1,023 individuals across the southeastern United States. Participants were asked to rate their level of concern for a tornadic supercell moving toward two locations. They were also asked to name the direction tornadoes usually come from and travel toward in their counties. Results indicated significantly more concern about the radar reflectivity within the supercell than concern about the location of the hook echo. Additionally, the perceived directions of tornado paths across the region were inaccurate with 75% of the sample either not answering, indicating that they did not know the most common direction for tornado paths, or answering that tornadoes travel in uncommon or unrealistic path directions. The Atlanta metropolitan area was used as a case study to illustrate inaccurate perceptions of path directions.

KEYWORDS: North America; Broadcasting; Communications/decision making; Decision making; Geographic information systems (GIS); Societal impacts

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Corresponding author: Jason Senkbeil, jcsenkbeil@ua.edu

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AFFILIATIONS: Senkbeil—University of Alabama, Tuscaloosa, Alabama; **Sherman-Morris and Vaughn**—Mississippi State University, Mississippi State, Mississippi; **Skeeter**—University of Delaware, Newark, Delaware

We continue to experience high fatalities from tornadic events despite improvements in forecasting technology, predictive methods, and increased cooperation between meteorologists and social scientists about risk communication products and messaging. The intensity of tornado outbreaks and property destruction is likely to continue an increasing trend (Brooks et al. 2014; Elsner et al. 2014; Tippett et al. 2016; Elsner et al. 2019; Moore 2021). Therefore, the importance of generating accurate forecasts and communicating those forecast details in ways that incentivize people to plan and take protective action is becoming increasingly critical to safeguard lives and property as tornado risk is a greater concern than ever.

As research yields more knowledge about tornadogenesis and the environmental conditions necessary for tornado outbreaks, greater confidence can be placed in forecast skill and predictability. The increased forecast skill and predictability must be paired with recommendations from social scientists to maximize the potential of communication to reduce the casualty rates from tornadoes (Fricker 2020). Greater confidence in predictability across the operational meteorological community has led to the development and potential implementation of programs such as Forecasting a Continuum of Environmental Threats (FACETs; Rothfusz et al. 2018). FACETs features probabilistic hazard information at time scales from days to minutes before weather and water events, and it is designed to be an enhanced and more helpful approach in weather risk communication. Until it or a similar system is used operationally, current tornado warning polygons will continue to be issued by the National Weather Service and communicated live primarily by broadcast meteorologists during wall-to-wall tornado warning coverage. Polygons are also displayed in weather apps, often without interpretation as would be true of broadcast coverage.

Due to the current use and reliance on tornado warning polygons, research has focused on themes related to risk perception and interpretation of polygons. Ash et al. (2014) tested the perceived fear and likelihood of taking protective action using the current polygon against hypothetical polygons with varying colors and shading gradients to determine the optimal polygon graphic format. The results concluded there was a trade-off in design; the current polygon with a red border caused more people to indicate they would take protective action while designs showing a color or shade gradient caused people closer to the center of the polygon and probable tornado to indicate a greater threat while decreasing the threat for those located on the polygon edges. A similar effect on protective action results was reported by Miran et al. (2018) when comparing locations in the tornado's path versus 5 miles away. Lindell et al. (2015) and Jon et al. (2018) also confirmed that the center of the polygon had greater concern and higher strike probabilities while Jon et al. (2018) additionally found strike probability judgments improved when the polygon was used with a radar image. Later research also found that three geospatial framing effects influence risk perception: 1) distance from the tornado path, 2) warning polygon inclusion or exclusion, and 3) color-coded uncertainty information (Klockow-McClain et al. 2019). Taken together, these results are in good agreement that most people correctly interpret that the center of the tornado warning polygon is generally the location with the greatest risk regardless of the graphic format. While it is necessary to ensure that more people closer to the probable tornado are taking protective action, it is an unwanted outcome to have people within the lower-risk parts of the polygon ignoring the warning due to path uncertainty and the possibility of more direct impacts than anticipated. These same principles apply to the perceptions of hurricane track forecasting using the cone of uncertainty or alternative graphics (Broad et al. 2007; Radford et al. 2013; Wu et al. 2013; Sherman Morris and Antonelli 2018; Senkbeil et al. 2019). A common theme of the hurricane cone of uncertainty research is a basic understanding of higher risk associated with proximity to the track line in the center of the cone with lower risk and sometimes confusion and misinterpretation about the meaning of the cone.

Despite the general success of warning polygons, not everyone is able to spatially estimate their risk by looking at maps with tornado warning polygons. When Oklahoma residents were asked to remember if they were located within tornado polygons during recent tornado outbreaks, over half the respondents indicated a false positive, meaning they perceived to be inside a tornado warning polygon when they were not (Krocak et al. 2020). One item that can improve comprehension and protective action decision-making for tornado warning polygons is using them in conjunction with radar images (Jon et al. 2018). Other results involving radar images, found that people were more likely to call someone they know in the path of a tornado while watching local television weather coverage when viewing a radar image with the meteorologist offscreen (Sherman-Morris and Lea 2016). The spoken message of locations at highest risk was believed to be the most important factor for viewers taking protective action even when the location was not shown on a map (Sherman-Morris and Lea 2016). Additional factors may also inhibit or enhance the interpretation of information from tornado warning polygons.

One possible factor that may affect interpretation is the influence of background knowledge about tornado meteorology and climatology at the county level. Residents of central Oklahoma generally displayed greater risk perceptions if they had been in closer proximity to an intense and recent tornado with evidence of stronger results where tornado paths have directly impacted locations (Johnson et al. 2021). People from counties with higher tornado activity and more tornado experiences generally demonstrate greater background knowledge about their true (climatological) tornado risk (Allan et al. 2020). This is also supported by Ellis et al. (2018), who found that previous tornado experience was associated with correct estimation or overestimation of climatological tornado risk, although Tennessee residents generally underestimated their tornado risk especially after accounting for missed tornadoes. Additional research has shown that college students from high-risk tornado counties significantly overestimated their actual tornado risk when compared to students from less active tornado counties (Senkbeil et al. 2019). Furthermore, incorrect perceptions and underestimation about winter tornado risk and nocturnal tornado risk were also common in the southeastern United States (Ellis et al. 2019; Broomell et al. 2020). Additionally, residents of Tennessee, Mississippi, and Alabama frequently believed tornado myths about protection from hills, topography, water bodies, or human-altered land features (Klockow et al. 2014; Ellis et al. 2019). Results from these studies sometimes have contrasting conclusions due to differences in methodologies and samples, but it is generally agreed upon that climatological tornado risk perception by the public is inadequate and needs improvement in order to enhance communication and better inform protective action decision-making.

It is hypothesized that individuals with greater knowledge and memory of past tornado tracks, intensity, frequency, and seasonality of occurrence may show heightened risk perceptions about tornado warning polygons and radar imagery. A potential latent area of research is how past tornado tracks and knowledge about tornado paths and directions may influence tornado risk perceptions and protective action decision-making. Although perception of tornado climatology has been compared to actual tornado risk, perception of tornado track directions has not previously been compared to actual tornado path directions. Tornado path climatology was summarized for much of the eastern United States (Suckling and Ashley 2006). As expected, almost 70% of tornadoes originate in the west, west-southwest, or southwest azimuthal directions between 270° and 225°. Notable exceptions include parts of the northern United States during summer, and also tornadoes generated by landfalling tropical cyclones.

In this research public knowledge of tornadoes was evaluated for over 1,000 residents of the southeastern United States. Specific research questions include the following:

1) Given the choice between two locations threatened by a tornado warning, can participants identify which location in a radar image has the greatest risk of being directly impacted by a tornado?
   (i) Is risk perception influenced by the presence of a tornado warning polygon?
2) Do participants have accurate spatial knowledge of the most common climatological tornado path directions in their counties?
3) Do participants with more accurate knowledge of tornado path directions also have better radar image perception accuracy?

Methods

Data collection and questions. A sample of 1,023 participants was recruited using Qualtrics, an online electronic survey panel with a membership of registered users. We used criteria for age, zip code, education, and gender to obtain a reasonably representative sample of our study area with respect to those characteristics. The sample of residents was restricted to zip codes of the southeastern United States (Alabama, Arkansas, Georgia, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee). Zip codes were used to confirm at least 30%–40% of participants were from rural areas to ensure that certain cities were not oversampled, and also to meet a project goal outside the scope of this article. Other quotas were set to provide an approximately equal ratio of those identifying as male and female, at least 50% with an education level of some college or less, and an age distribution evenly split among generational categories because these demographics have been previously associated with risk perception or weather information usage. Participants were asked about race/ethnicity, but it was not used as a screening variable, and as a result, the proportion of participants identifying as White (82.9%) was greater than the populations of most of the states within the study area. Time of residence in their home county was also asked to better understand familiarity with local geography. Sample characteristics are provided in Table 1.

Questions used to measure radar image perception accuracy in this research followed measures based on Demuth et al. (2018), whose questions aimed at quantifying the extent to which a respondent had personalized the risk from a previous tornadic event. The questions were modified to consider the hypothetical nature of the survey and to fulfill objectives for this research and related projects. Participants in our study were asked to view a radar image of a supercell and indicate to what extent they would worry or how likely they were to take action or be affected by a tornado at either point A or point B. One image featured both points A and B within a tornado warning polygon while the other was the same image with the polygon removed (Fig. 1). Point A was situated at the approximate location that was to be impacted by the core of highest radar reflectivity and point B was to be directly impacted by the hook echo as demonstrated by the arrow indicating the path of the supercell. Thus, our goal was to assess the accuracy of risk perception for points A and B and also to determine if the presence of a polygon had any relationship with enhanced risk perception. Participants

Table 1. Sample characteristics. *N* varies for each question since not all 1,023 participants answered every question. sd = standard deviation.

Demographic question	Answer or category	Percentage
State in which participants live (*N* = 1,019)	Alabama	15.7%
	Arkansas	7.8%
	Georgia	35.3%
	Kentucky	3.7%
	Louisiana	2.9%
	Mississippi	7.9%
	Missouri	4.7%
	Tennessee	22.0%
Whether zip code was classified as urban or rural (*N* = 1,019)	Rural	34.5%
	Urban	65.5%
Highest level of education completed (*N* = 1,023)	Some high school	3.5%
	High school diploma or GED	23.8%
	Some college, technical school, or associate	29.8%
	Bachelor's degree	19.4%
	Advanced degree	22.7%
	Prefer not to answer	0.9%
Gender (*N* = 1,023)	Female	51.1%
	Male	47.9%
	Other responses	1.0%
Age (*N* = 1,023)	Min: 18; max: 92; avg: 44.5 (sd: 16.8)	
Time of residence in county (*N* = 1,019)	75%: 5 years or more; 44%: 20 years or more	

were asked to rank their worry or likelihood on a scale from 1 to 5 with 1 being the highest for the following questions for the radar images:

> To what extent would you worry about loved ones if they were located at point A [point B]? (Referred to as loved ones question hereafter.)
>
> To what extent would you worry about your house if it were located at point A [point B]? (Referred to as house question hereafter.)
>
> How likely would you be to take action to protect yourself or your loved ones if you lived at point A [point B]? (Referred to as protective action question hereafter.)
>
> How likely do you think it would be for the tornado to affect point A [point B]? (Referred to as tornado impact question hereafter.)

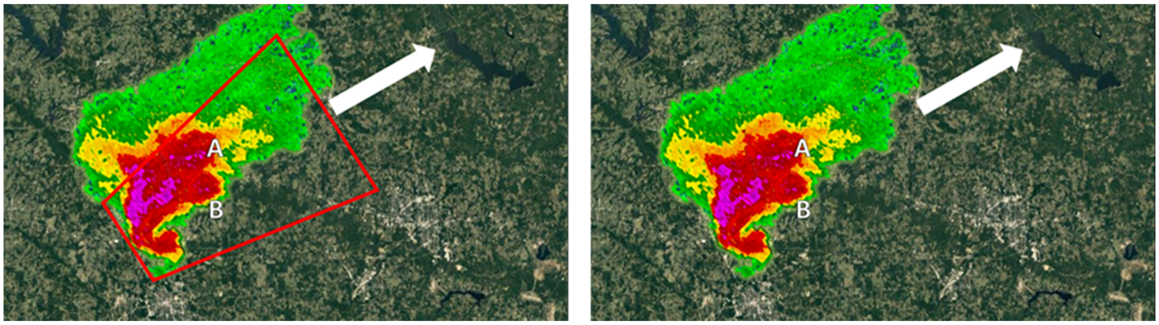

Fig. 1. Supercell radar image (left) with polygon and (right) without polygon. The location of point A was designed to be impacted by the highest radar reflectivity and point B the hook echo.

Two questions were used to measure the perceptions of tornado path direction accuracy. Participants were asked, "In your experience, do the tornadoes that threaten your county seem to come from any one particular direction most often?" If they answered "yes," then participants were instructed to name the direction that tornadoes usually come from and what direction tornadoes usually travel toward in their counties. Measures for the path direction questions were based upon hurricane track perception research (Senkbeil et al. 2020) but modified for climatological tornado risk perception objectives after Ellis et al. (2019) and Senkbeil et al. (2019). Tornado path direction perception accuracy was assessed for the entire study area, but some variance in the most common climatological paths exists across such a large region. For this reason, the Atlanta, Georgia, metropolitan area was selected as a case study since it represented the largest number of our participants while minimizing variance in climatological tornado path directions.

Data analysis. For research question 1, the radar image questions were tested using a series of Wilcoxon signed-rank (WSR) tests. All of our Likert scale responses were nonnormally distributed, and thus, WSR tests were used to compare two paired nonparametric ordinal groups of responses for each question. The test is a comparison of the sum of the ranks associated with positive and negative differences between the groups with the null hypothesis being that the probability of a positive difference is equal to the probability of a negative difference (Wilcoxon 1945). Comparisons were made between points A and B for the loved ones, house, protective action, and tornado impact questions for the supercell image with a polygon and without a polygon (see Fig. 1).

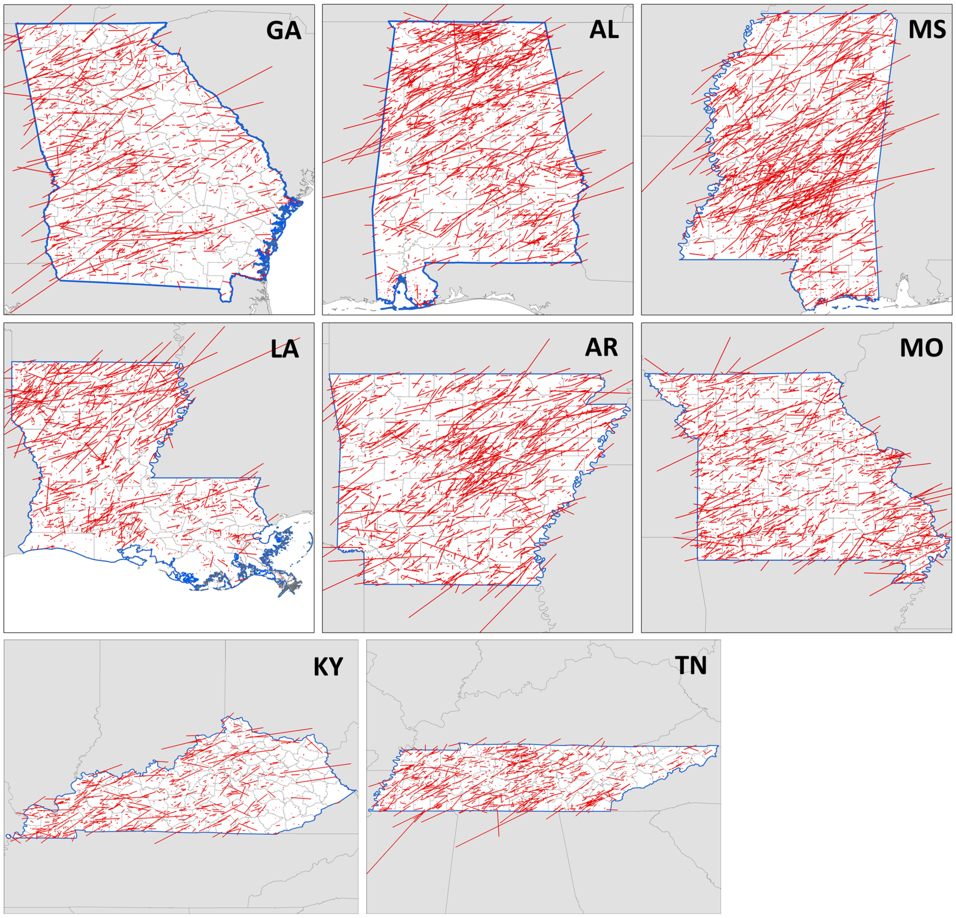

Fig. 2. Historical tornado paths (1950–2018) for each state in the study area. Source: SVRGIS Storm Prediction Center.

For research question 2, tornado path direction questions were approached from a qualitative and descriptive statistic methodology. The perceived tornado tracks of each participant were grouped into directions tornadoes travel from (origin) and directions tornadoes travel to (destination) using the eight directions of N, NE, E, SE, S, SW, W, and NW. All of the historic tornado tracks from the Storm Prediction Center's SVRGIS archive were then mapped across the eight-state region for a qualitative comparison with the percentages over the period 1950–2018 (Fig. 2). Percentages of each unique direction combination were tabulated for the entire study region to determine overall tornado path perception accuracy compared to the actual tracks from SVRGIS.

Continuing with research question two, while the comparisons across the entire region are useful, it was hoped that a more detailed spatial analysis of tornado path directions could provide a better evaluation of the risk perception accuracy of tornado path directions. The Atlanta metropolitan area was used as a case study. Similar to above, SVRGIS was used to map

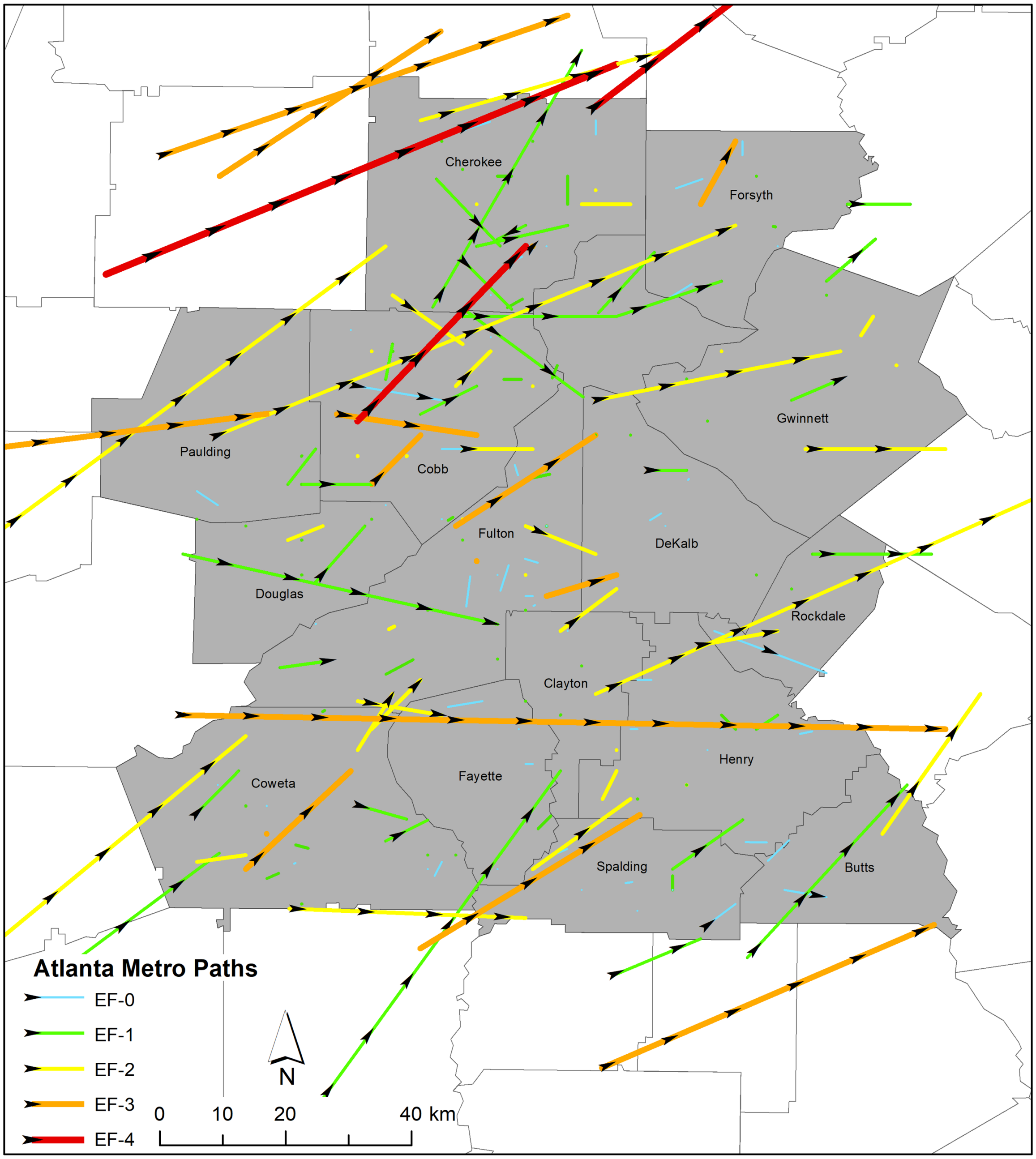

Fig. 3. Historical tornado paths (1950–2018) for Atlanta metropolitan counties. Arrows were placed on the tracks > 5 km to see direction of motion. Source: SVRGIS Storm Prediction Center.

the tracks of only the counties surrounding Atlanta (Fig. 3). A smaller spatial area allowed for arrows to be labeled onto the tornado paths to see the direction of travel, although this was limited to only tornadoes with pathlengths in excess of 5 km for ease of interpretation. Percentages were then calculated for each of the eight perceived direction origins. Then within each of the eight perceived origins, each unique direction percentage was also calculated. For example, for the NW origin a percentage was calculated for all of the participants that answered from the NW, and then within the NW origin there could be NW to SE, or NW to E, or NW to W, etc. Each image was created using GIMP image editing software.

For research question 3, two groups were created for participants that had realistic or acceptable (RA) tornado path direction perceptions and unrealistic or uncommon (UU) tornado path direction perceptions. The radar image location responses from research question one were collected for each tornado path direction perception group. Following the same procedure for research question one, comparisons were made between points A and B for the loved ones, house, protective action, and tornado impact questions for the supercell image with a polygon and without a polygon (see Fig. 1). The tornado path direction perception groups were compared using Mann–Whitney tests due to ordinal responses and these groups being independent instead of paired.

Results and discussion

Radar image perception accuracy. Eight WSR tests for significant differences were conducted for the questions about worry or likelihood between points A and B for both the polygon and no polygon radar images. Point A was designed to show where the highest radar reflectivity would occur compared to the location in the path of the hook echo at point B, which was intended to represent the highest risk area for tornado impact. All tests were significant at $p < 0.05$ ($p < 0.001$) (Table 2) for more worry or greater likelihood at point A compared to point B. The no polygon responses showed the same or slightly less worry or likelihood

Table 2. Wilcoxon signed-rank test results for differences in worry or likelihood between points A and B in Fig. 1. Responses were from 1 to 5 with 1 indicating the greatest worry or likelihood. sd = standard deviation. There were no statistically significant differences between polygon vs no polygon tests.

Questions point A vs point B	Point A polygon				Point B polygon		
	p	*n*	Mean	sd	*n*	Mean	sd
To what extent would you worry about loved ones	<0.001	494	1.54	0.90	492	1.84	0.980
To what extent would you worry about your house	<0.001	491	1.70	0.97	493	1.93	1.010
How likely would you be to take protective action	<0.001	491	1.63	0.97	490	1.84	1.000
How likely do you think it would be for the tornado to affect	<0.001	491	1.70	1.00	490	1.92	0.990
Questions point A vs point B	**Point A no polygon**				**Point B no polygon**		
	p	*n*	Mean	sd	*n*	Mean	sd
To what extent would you worry about loved ones	<0.001	527	1.61	0.99	527	1.96	1.08
To what extent would you worry about your house	<0.001	528	1.71	1.02	525	1.97	1.07
How likely would you be to take protective action	<0.001	527	1.69	0.99	528	1.94	1.09
How likely do you think it would be for the tornado to affect	<0.001	527	1.77	1.05	527	2.03	1.10

than the polygon responses for each question with no statistically significant differences; however, the polygon had some practical influence with slightly more worry or likelihood inside a polygon. These findings are surprising considering the high tornado activity across the region, length of residence time for the majority of our participants, and wall-to-wall tornado warning coverage in many television markets. The television coverage in many markets describes supercell morphology in detail often circling and referencing the hook echo with clear explanations of where the tornado is located. Given that local television coverage is the preferred source of information (Sherman Morris and Lea 2016) it was expected that more participants would indicate greater worry or likelihood for point B. Additionally, Saunders et al. (2018) found that radar was considered most useful to residents of the southern and south-central United States; thus, it is assumed that people in our study region rely on radar more often than in other regions.

These results suggest that the participants in our sample seem to be responding more to supercell radar colors they think indicate the greatest threat, instead of radar presentation of supercell morphological characteristics. Previous related research on color interpretation for storm surge in hurricanes (Sherman-Morris et al. 2015) and for color shading in tornado warning polygons (Ash et al. 2014) provides evidence to support this conclusion. There are other possible explanations for the results. For example, perhaps

Table 3. Path direction perception results for the entire eight-state study region.

1) In your experience, do the tornadoes t hat threaten your county seem to come from any one particular direction most often?	*N* = 1,023
Yes	47.4%
No, or I am not sure	52.6%
2) From what direction do tornadoes in your county usually come from and what direction do they travel to?	Yes to question 1 (*n* = 485)
Realistic or acceptable path directions	53.4%
Unrealistic or uncommon path directions	46.6%
SW to NE (the most accurate answer)	17.9%
Answered from and to as the same direction	16.3%
Realistic or acceptable path directions	Percentage
SW to NE	17.9%
W to E	12.8%
S to N	5.4%
S to NE	3.9%
W to NE	3.5%
S to E	2.9%
NW to E	2.7%
NW to SE	1.4%
SW to E	1.2%
W to SE	0.8%
SW to N	0.4%
W to N	0.4%
Unrealistic or uncommon path directions	Percentage
S to S	7.2%
E to W	3.1%
S to W	2.3%
SE to SE	2.1%
E to E	1.9%
S to SE	1.6%
N to N	1.4%
N to S	1.4%
NE to NW	1.4%
SE to NW	1.4%
NE to N	1.2%
NE to NE	1.2%
SE to NE	1.2%
NW to NE	1.2%
N to NE	1.0%
W to W	1.0%
31 path combinations < 1%	

many participants did not pay attention to the direction arrow in Fig. 1, or do not have a good perception of the direction that tornadoes typically travel and therefore did not assume forward movement of the storm? Perhaps some participants felt that either letter A or B was closer to the center of the polygon near the highest perceived risk (Ash et al. 2014; Lindell et al. 2015; Jon et al. 2018; Klockow-McClain et al. 2019), even though letters A and B are equidistant from the lengthwise midpoint of the polygon? Perhaps some participants thought that letter A was closer to being affected by any part of the storm and thus at greatest risk? We cannot assign attribution of our results without additional questions and continued research. It is hoped that interview research in progress will bestow greater confidence and explication of these results. It can be preliminarily concluded that greater attention should be devoted to increased radar education for the general public since the proliferation of radar apps and sources is so widespread.

Tornado path direction perception accuracy. Of the 1,023 participants, 485 (47.4%) answered "yes" to the question, "In your experience, do the tornadoes that threaten your

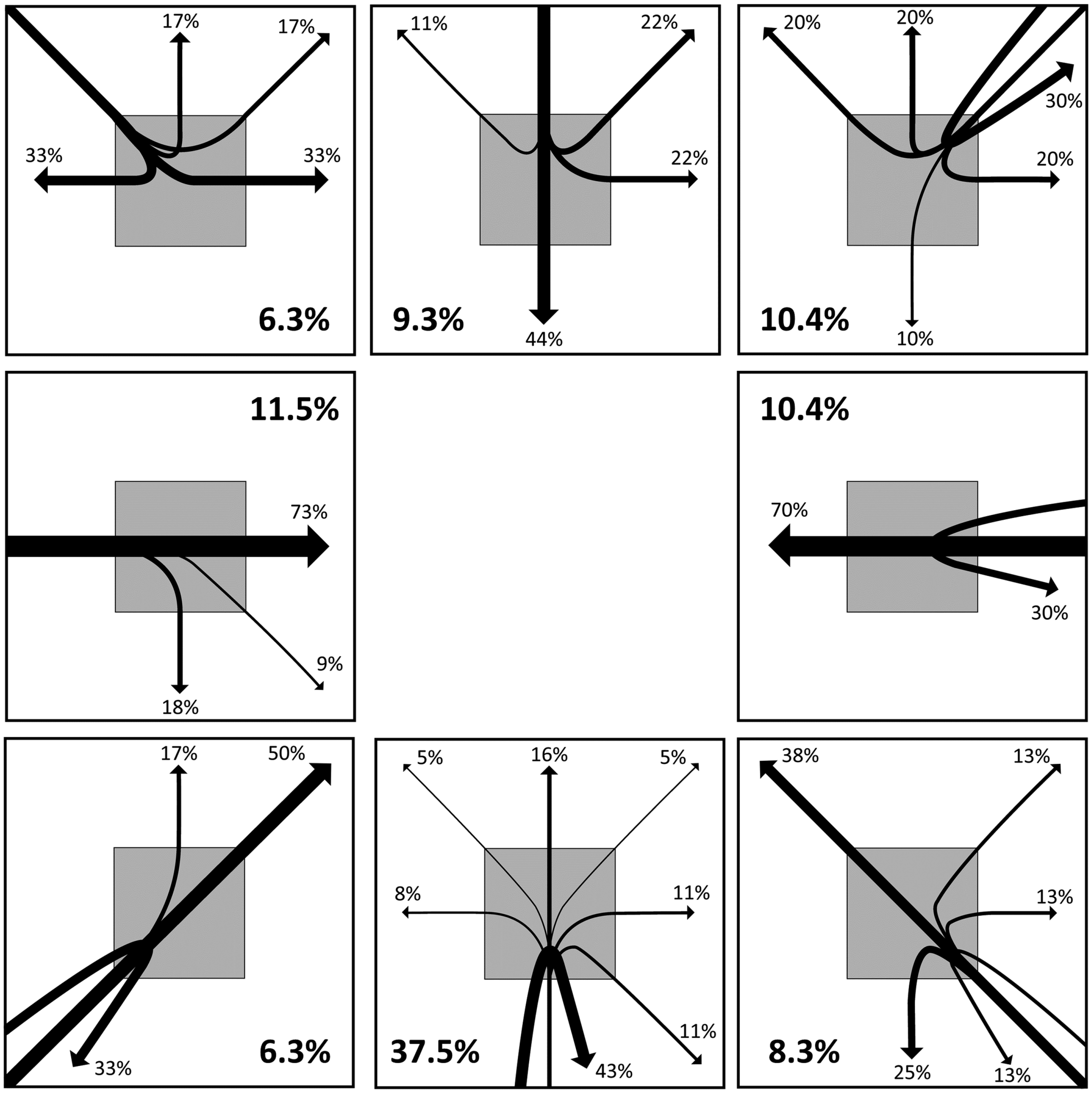

Fig. 4. Perceived path directions of participants from Atlanta metropolitan counties organized by origin direction on a hypothetical polygon. The large boldface number in the corner represents the percentage of participants that chose an origin from that direction. The smaller numbers on the paths represent the destination direction percentages. (top) NW, N, and NE origins. (middle) W and E. (bottom) SW, S, and SE.

county seem to come from any one particular direction most often?" This indicates that 52.6% of the participants answered "no," or "I am not sure," which already creates a majority that did not demonstrate accurate spatial knowledge of tornado path directions in their counties. The inaccuracy percentage grows when further subdividing the answers of "yes" participants.

The 485 "yes" participants were asked to name the direction tornadoes come from and direction they travel to. The historical tornado paths for the eight-state region were mapped to show the general spatial pattern of track orientations (see Fig. 2). The dominant path direction for tornadoes is an origin in the west or southwest (Suckling and Ashley 2006). This is especially true for stronger and longer-track tornadoes. QLCS and bowing segments can sometimes produce tornado paths with origins from the northwest while some longer-track tornadoes can have an origin closer to a southerly instead of southwesterly direction. Tropical cyclone tornadoes often come from a southeast or easterly direction, especially in coastal counties bordering the Gulf of Mexico if the tropical cyclone is moving west or northwest. We had a small number of participants from these coastal counties. Tornadoes originating from the northeast or north would be extremely rare in this region. Therefore, origins from the NW (315° azimuth), W, SW, and S (180° azimuth) were grouped together and considered RA points of origin for perceived tracks. Origins from the SE, E, NE, and N were considered UU points of origin for perceived paths. Each path combination of origin and destination within these two groups was then calculated.

Results for the entire "yes" sample display a variety of origin and destination directions for tornado paths (Table 3). Of the 485 participants, 53.4% were grouped into the RA path group. When considering the large number of "no" and "I am not sure" responses and the total sample of 1,023, the percentage of acceptable path direction combinations shrinks to 25% of the total sample that had an RA perception of common tornado path directions. The most common perceived path answer of SW to NE is the best answer, but that was only 17.9% of the "yes" participants and only 8.5% of the total sample (see Table 3). Of particular note, were egregiously inaccurate responses of origin and destination being the same direction, essentially meaning the tornado would travel in a loop. A total of 16.3% of the "yes" responses were origin and destination as the same direction, which almost offsets the 17.9% that correctly answered SW to NE. A closer inspection of tornado path direction perception for the Atlanta metropolitan area was performed to better understand any possible contamination of these results due to mild spatial variability of climatological tornado path directions across the eight-state region.

Perception of tornado paths for Atlanta metropolitan area counties. The climatological tornado paths for Atlanta metropolitan counties are shown in Fig. 3. Arrows were placed in Fig. 3 for all paths greater than 5 km to facilitate viewing. Paths less than 5 km were too short to mark with arrows and still view the path. The majority of climatological paths were from the SW to NE, or from the W to E. There were also paths with origins in the S and NW, confirming the broader classification and results from the previous section for what is considered RA for path directions. There were four tornadoes with odd origins from the NE, E, or SE and all of these were EF0 or EF1 with short tracks.

The Atlanta metropolitan area was presented as one hypothetical area for the mapping of perceived tornado paths (Fig. 4). The perceived paths are uniformly distributed for all direction of origin, except for the south. An origin in the south was the most common answer with a scattered array of destinations for paths and the largest percentage being south to south. Other direction origins also have high percentages of the same path direction for origin and destination, which aligns with the overall sample results. Only 6.3% answered an origin in the SW and of that number only half said SW to NE. This is proportionally less accurate than the broader sample results, providing more confidence to conclude that many people in tornado prone areas of the southeastern United States may have poor knowledge of directionality in general, and of climatological tornado path directions. Poor directional knowledge would immediately place individuals at a disadvantage when making timely and confident protective action decisions under a tornado warning. Likewise, poor knowledge of common tornado path directions, especially for stronger tornadoes, similarly places individuals at a disadvantage making protective action decisions with confidence.

Do participants with more accurate knowledge of tornado path directions also have better radar image perception accuracy? Eight Mann–Whitney tests for significant differences between path direction groups (RA or UU) were conducted for the questions about worry or likelihood between points A and B for both the polygon and no polygon radar images (Table 4). Participants in the RA tornado path direction perception group did not have better radar image perception accuracy than participants in the UU group. The two significant results between the RA and UU groups (Table 4), largely parallel the WSR test results (Table 2), after a Bonferroni correction. There was significantly more worry about their houses and likelihood of tornado impact in the RA group for location A in the polygon image. There were no significant results for point B for the polygon or no polygon image. Although some participants have better knowledge of climatological tornado path directions, this knowledge is not

Table 4. Mann–Whitney test results for differences in worry or likelihood between points A and B in Fig. 1 for the groups of realistic or acceptable (RA) and unrealistic or uncommon (UU) tornado path direction perception. Responses were from 1 to 5 with 1 indicating the greatest worry or likelihood. Boldface indicates significant differences at $p < 0.05$ after a Bonferroni correction ($p < 0.006$).

	p	RA path group mean	UU path group mean
Polygon image			
Location A			
To what extent would you worry about loved ones	0.180	1.37	1.45
To what extent would you worry about your house	**<0.001**	1.48	1.83
How likely would you be to take protective action	0.008	1.43	1.68
How likely do you think it would be for the tornado to affect	**0.004**	1.51	1.81
Location B			
To what extent would you worry about loved ones	0.937	1.78	1.73
To what extent would you worry about your house	0.261	1.81	1.87
How likely would you be to take protective action	0.342	1.74	1.80
How likely do you think it would be for the tornado to affect	0.763	1.84	1.87
No polygon image			
Location A			
To what extent would you worry about loved ones	0.824	1.50	1.50
To what extent would you worry about your house	0.115	1.57	1.75
How likely would you be to take protective action	0.019	1.57	1.76
How likely do you think it would be for the tornado to affect	0.021	1.60	1.86
Location B			
To what extent would you worry about loved ones	0.579	1.80	1.81
To what extent would you worry about your house	0.167	1.81	1.91
How likely would you be to take protective action	0.394	1.83	1.92
How likely do you think it would be for the tornado to affect	0.253	1.88	2.01

accompanied by more accurate knowledge about storm morphology and the most dangerous location within a supercell radar image.

Conclusions and recommendations

This research shows two concerning results: 1) people were significantly more concerned about the radar reflectivity or colors associated with precipitation than they were about the location of the hook echo in a supercell radar image and 2) only a quarter of our sample had RA perception and knowledge of tornado path directions in their counties. The path direction results only improve to 53% RA when only using the "yes" answers to our question about tornadoes in their county coming from a certain direction. If these percentages in our sample are representative of the population, then greater than 50% of the residents of our eight-state study region are at a serious knowledge deficit regarding tornado climatology before a tornado warning is issued for their zip code. Furthermore, participants with more accurate knowledge of path directions did not also have more accurate knowledge of the most dangerous part of a supercell in a radar image.

Knowing the location of the tornado when viewing a radar image can reduce anxiety and also improve decision making. Conversely, it may also cause a realization of urgency if people know they are directly threatened by the most dangerous part of the polygon. Furthermore, knowledge of directionality and tornado paths could enhance the precision and speed of decision making and could supplement cognition of radar images. This knowledge could be life-saving.

While the results are important findings to consider for weather communication moving forward, limitations of our work exist. The first and most important is the way the path direction question was asked using a "from and to" method. Some participants may have been unable to think about that spatial representation mentally, but could have performed better if asked about path directions in a different way. In ongoing and related interview research, participants are asked to draw their perceived tornado tracks on a paper map. Participants have been more successful drawing tracks in our preliminary results, but this has been a smaller and more educated sample in a county with high tornado activity. Furthermore, while these interview participants have been more accurate in drawing tracks, some have drawn a southwest-to-northeast path orientation but could not identify what direction that was from and to. "I know they come into the county like this and then go this way but I don't know what direction that is" was a comment captured from four of our interview participants after drawing the best path orientation of southwest to northeast. More research and more case studies beyond Atlanta metropolitan counties are required before any broader conclusions can be reached about recommendations to address the possible lack of knowledge of tornado path directions found in this research. Our findings may draw attention to possible differences in communication and perceptions between graphical versus text products. Reading or hearing a text-based product with the from–to direction of movement of a tornado may not be as useful as graphical depiction of movement. For example, the from–to movement displayed along with a radar image for better veining of path direction may lead to better comprehension.

Regarding radar images, the design of Fig. 1 is common in operational use with a tornado radar polygon encompassing the conflated threats of potential large hail and also a tornado. It is hoped that polygon areas will continue to shrink to focus more on the tornado path and less on the reflectivity core as graphical tornado warning communication evolves in the future. Furthermore, the locations of letters A and B in Fig. 1 could have been interpreted to indicate that either letter A or B would be impacted more directly or sooner. Speculation exists on other possible misinterpretations, but these questions cannot be answered until more research is conducted.

Another possible limitation is our 1–5 scale being ranked with 1 as the greatest worry or likelihood. This could have caused some participants to become confused and rank 5 as their greatest worry or likelihood. The possibility of any such confusion is minimized by consistent statistical results across all questions for both the polygon and no polygon results. A signal of persistent confusion would have likely diluted the statistical results and it did not.

Results of this research have implications for enhancing communication for both broadcast and operational meteorologists. Broadcast meteorologists should emphasize tornado path directionality more in attempts to educate their audiences during live tornado warning coverage and also off the air via social media. Operational meteorologists can use these path perception results to inform promotional campaigns on their local weather forecast office websites or emergency management websites and other public outreach sources. Broadcast meteorologists can also continue to emphasize storm morphology and tornado warning polygons during live coverage so that the public will become better acquainted with the location of a tornado in a radar image. We suggest that television markets in less active tornado areas follow the model of broadcast meteorologists from active tornado markets who do a thorough job of educating the public on storm morphology. Furthermore, it is suggested that broadcast meteorologists alternate their scale from street-level to storm-level coverage so that the public can get a better idea of storm morphology in relation to the polygon—many already do this. Additionally, operational meteorologists can target radar storm morphology education for the public with new initiatives or updates to existing educational materials. These simple recommendations could be easily implemented and modified as future research becomes more conclusive about suggestions for improvements.

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